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THE UNIVERSITY OF ALBERTA

SEDIMENT TRANSPORT IN TWO ROCKY MOUNTAIN STREAMS

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Sediment Transport in Two Rocky Mountain Streams," submitted by Gerald Charles Nanson in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

This thesis studies the pattern of sediment transport in two small streams in the Canadian Rocky Mountains, relating sediment transport to water discharge. Bed-load measurements are made using low weirs to trap sediment in both Two O'Clock and Bridge Creeks and in addition, bed-load basket sampler measurements and suspended load samples are taken in Bridge Creek.

Weir sedimentation results for measuring bed-load transport in Two O'Clock Creek show a close relationship between bed-load discharge and water discharge. The analysis of basket sampler results from Bridge Creek illustrates that the bed-load discharge/water discharge ratio is greater prior to the season's peak flow than after this peak. As a result, two bed-load rating curves are used in Bridge Creek, and both these show a close relationship between water discharge and bed-load discharge. The critical water discharge required to entrain bed-load in Bridge Creek rose significantly after the peak flow.

Tentative basket sampler efficiencies determined from basket sampler and weir survey results on Bridge Creek indicate an increase in sampler efficiency as water and sediment discharge increase.

Four commonly used bed-load formulae are applied in both Bridge and Two O'Clock Creeks to predict bed-load discharges. As a result of the poor relationship between the predicted values and the measured bed-load discharges, it is concluded that the general application of bed-load formulae to small mountain streams will not provide an accurate estimation of bed-load.

The analysis of suspended sediment concentration/water discharge ratios in Bridge Creek shows a progressive decrease as the runoff season progresses. While the relationship between sediment concentration and water discharge shows considerable variation, the explained variance can be significantly increased if the number of days between the start of the runoff season and the time of sampling is also included in the analysis.

On the basis of qualitative observations in Bridge Creek

catchment, the most plausible hypothesis to explain the decline of both bed-load and suspended load/water discharge ratios is the reduction of sediment supply to the stream channel. This supply is probably related to spring thaw geomorphic processes within the catchment.

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CHAPTER I

INTRODUCTION

1.1. Objectives

At present very little is known about the pattern of sediment transport in alpine streams. In this study sediment transport is measured in two small streams in the Canadian Rocky Mountains.

The objectives of the study are threefold:

a) To measure bed-load and suspended load and observe seasonal variations in the transport pattern.

b) To relate any changes that occur in the transport pattern to qualitative observations of geomorphic processes controlling sediment sources.

c) To compare measured bed-load transport rates with the results obtained from empirical bed-load formulae proposed by other workers.

Mountain streams such as the two under study are suitable for analysis for a number of reasons. Firstly, the streams are small and therefore relatively easy to handle with respect to the volume of bed-load which they transport in one season. Secondly, their basins are small and therefore can be studied in sufficient detail to determine generally where the sediment is coming from and what controls its supply. Thirdly, because of the presence of persistent snow fields that melt throughout the spring and summer, these small basins support almost continuous water flow throughout this period. This enables observations to be made of changes in sediment supply and sediment transport over time.

As a result of their relatively low discharges, these small streams can be considered to be nearly as manageable as a flume, yet having all the complexities of a field situation. Because of the high energy geomorphic environment provided in an alpine basin, processes within the catchment are rapid and relationships between these and the sediment transport characteristics are more readily determined.

1.2. The Field Area

The two streams selected for this study are Two O'Clock Creek and Bridge Creek. They are both left bank tributaries of the upper North Saskatchewan River (Figure 1.1.). The area is known as the Kootenay Plains and lies twelve miles east of the Banff National Park boundary on the David Thompson Highway (No. 11).

1.2.1. Physiography

The streams traverse two major contrasting physiographic areas (Figure 1.2.):

1) Steep mountain basins situated on the side of the North Saskatchewan River valley.

2) The broad alluvial fans which were deposited on the North Saskatchewan valley floor following the retreat of the last Wisconsin glacier (McPherson, 1970).

A minimum date of 9330 $\pm$ 170 years B.P. has been suggested for the final deglaciation of the area. This date is taken from a charcoal layer located near the Saskatchewan Bridge, 15 miles upstream from the field area (Westgate and Dreimanis, 1967). No exact date is available for the immediate field area.

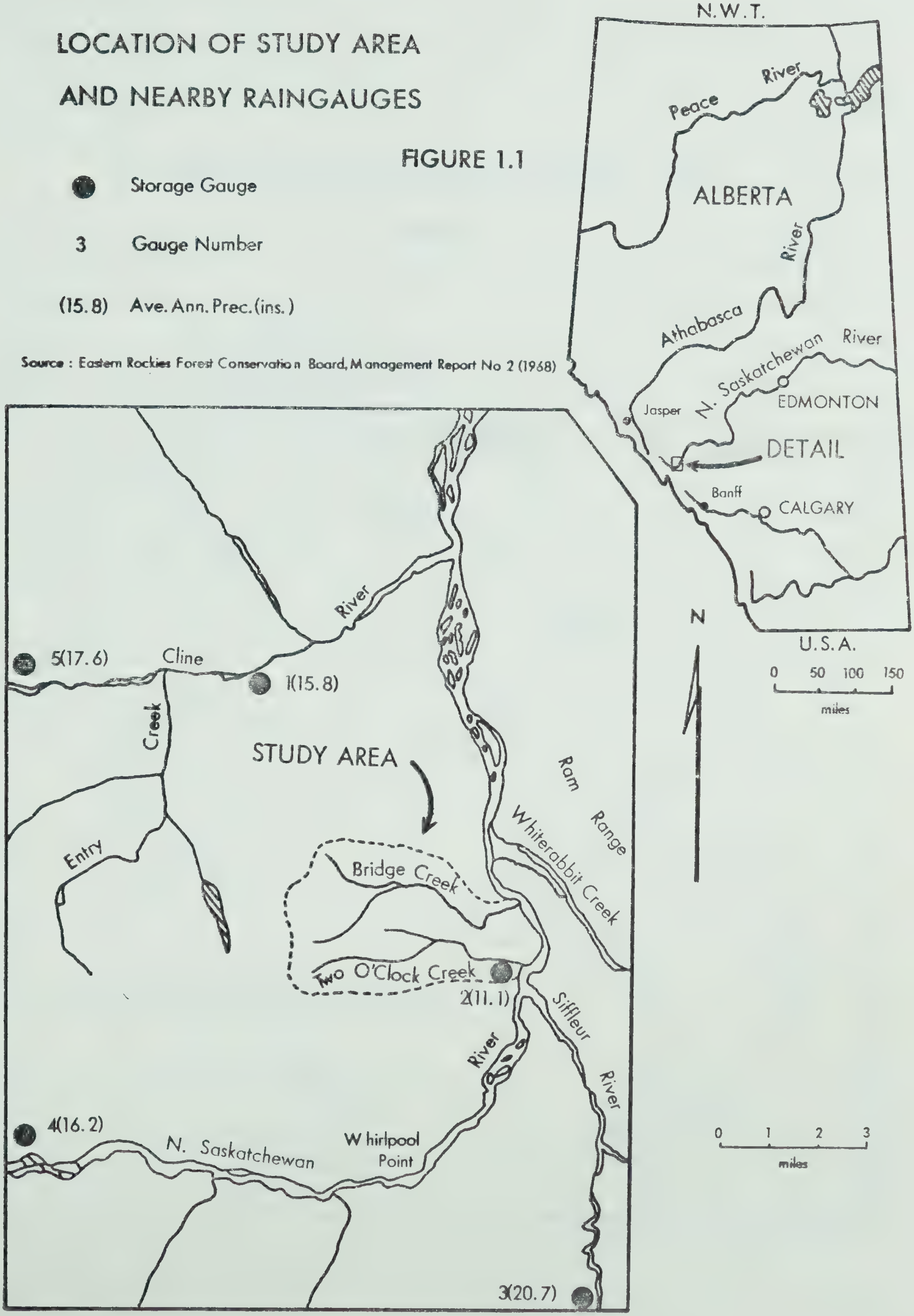
This study is concerned only with the catchment areas extending to the exit of each basin.

Two O'Clock Creek drains an area of 3.5 square miles. From the head of the basin to the Two O'Clock Creek-North Saskatchewan Junction is 4.8 miles along the channel and from the head of the basin to its mouth at the gauging site (Figure 1.2.) is 3.4 miles. The average stream gradient in the basin is 771 feet per mile and 332 feet per mile across the alluvial fan. The maximum elevation of the basin is 9,300 feet on the ridge at the head of the catchment and the basin exit is at an elevation of 4,330 feet (McPherson, 1971a).

Bridge Creek drains an area of 6.1 square miles with a maximum altitude of just over 9,000 feet at the head of the basin. The distance from the source of the stream to its exit from the catchment at the weir site (Figure 1.2.) is 5.2 miles along the channel and from the source to

LOCATION OF STUDY AREA AND NEARBY RAINGAUGES

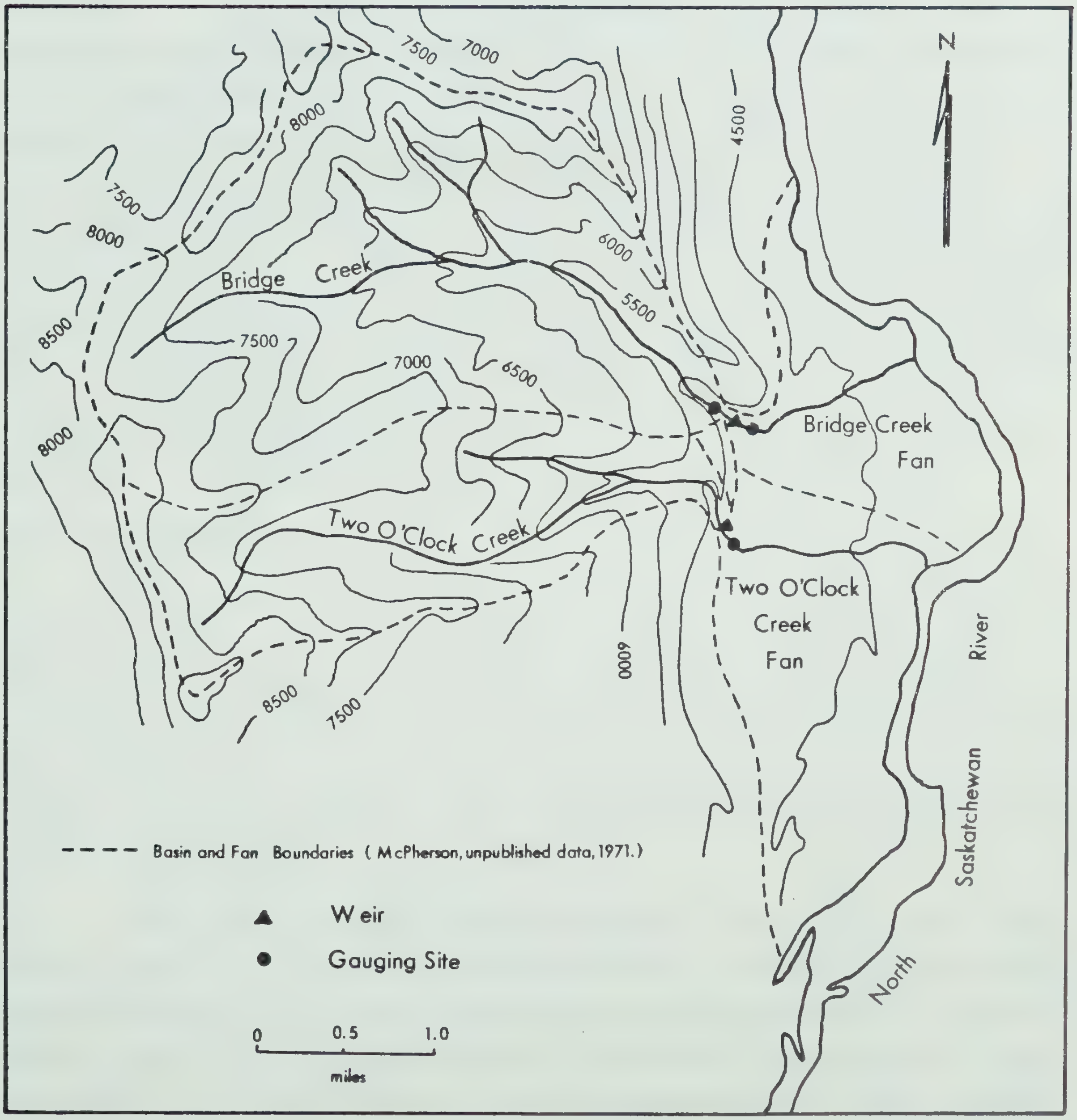
FIGURE 1.1



Source : Eastern Rockies Forest Conservation Board, Management Report No 2 (1968)

BRIDGE CREEK AND TWO O'CLOCK CREEK BASINS'

FIGURE 1.2



the stream's confluence with the North Saskatchewan River is 6.5 miles. The basin exit is at an elevation of 4,720 feet at the fan apex, giving a relative relief within the basin of approximately 4,280 feet. The average slope of the stream within the catchment is 533 feet per mile and across the upper part of the fan is 435 feet per mile.

Both basins contained tributaries of the North Saskatchewan glacier during the Pleistocene and as a result the lower portions of the basins below the tree line are mantled with till and fluvioglacial deposits. The tree line at 7,000 feet coincides approximately with the proposed maximum thickness of ice in the main valley system (McPherson, 1970). Above this elevation the slopes consist of bare rock, scree and colluvial material. In places, this material overlies the till.

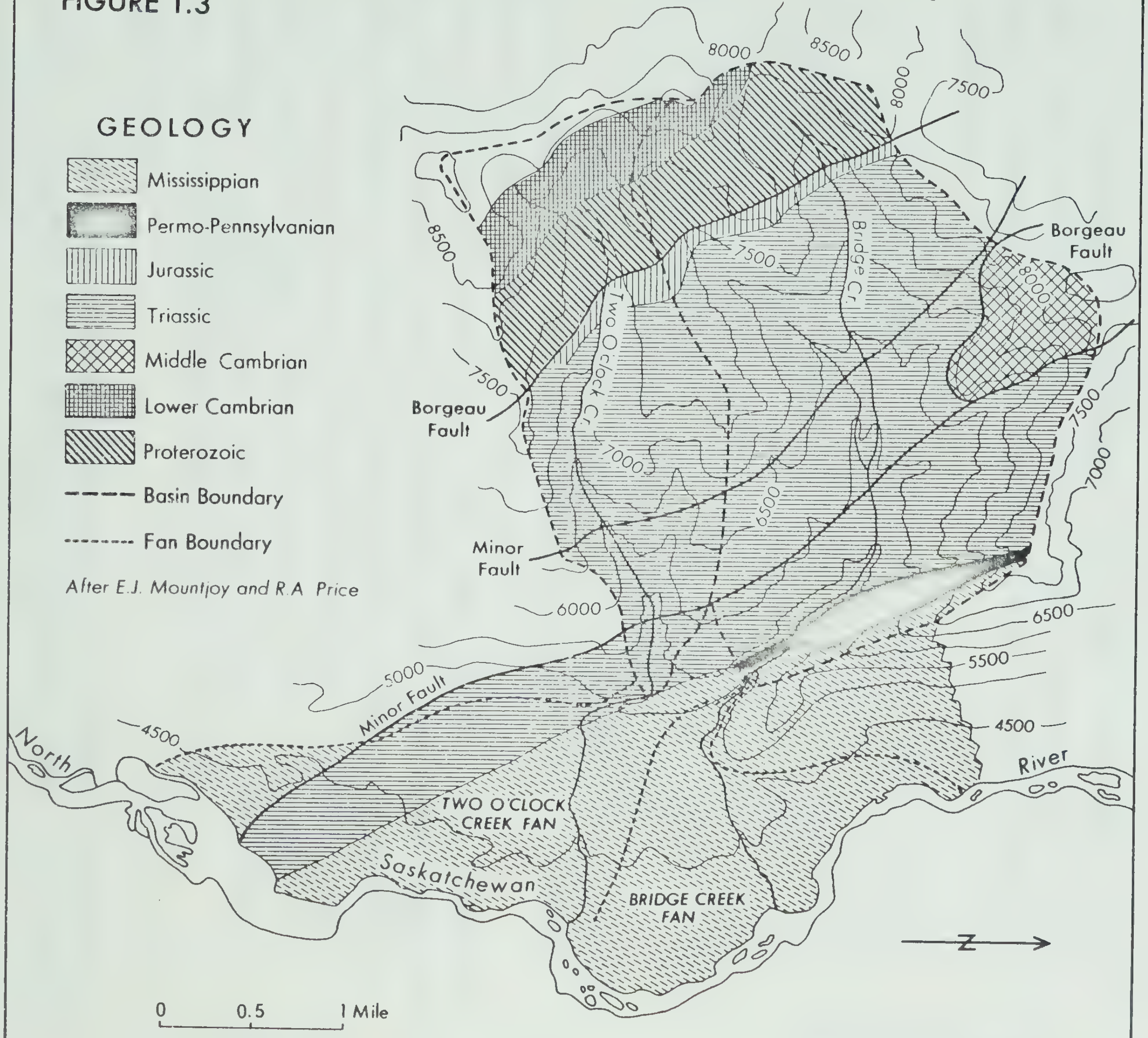
Since the Pleistocene, Two O'Clock Creek and Bridge Creek have cut steep-sided inner gorges into these accumulated sediments to a depth of over 150 feet in places. From observations in the field it appears that these streams are now running on the original bedrock valley floor or on a thin mantle of alluvium covering the floor. At a number of locations the streams have cut into the bedrock, particularly at the position of waterfalls along each profile.

1.2.2. Bedrock Geology

The study area is underlain by sedimentary rocks of the Main Ranges and Front Ranges Subprovinces, the rocks of which vary in age from Jurassic to Proterozoic (Figure 1.3.). These two Subprovinces are separated along a massive series of thrusts classed together as the Main Ranges Fault Zone. Ranges in both Subprovinces are roughly parallel and assume an alignment generally from the northwest to the southeast (North and Henderson, 1954).

The lower portions of Bridge and Two O'Clock basins are underlain by rocks of the Front Ranges Subprovince. The Borgeau Thrust Fault, trending northwest southeast, intersects the stream channels at approximately 7,300 feet. The upper parts of the basins above this altitude are underlain by rock occurring in the transitional belt along the Main Ranges Thrust Zone. Along the Borgeau fault the older Proterozoic beds have overridden the strata of the Middle and Upper Palaeozoic and Lower

FIGURE 1.3



Source : McPherson, (unpublished , 1971.)

Mesozoic (Verrall, 1968). According to recent studies by Price (unpublished), reported by Hirst (1971), the succession from the top of the divide at the head of the two basins, to the basins' exits is as follows: Stephen, Cathedral, Gog, Miette, Fernie, Spray River, Rocky Mountain and Rundle.

Lithologically, limestones and dolomites are dominant with quartzites, sandstones, slates, shales, pebble conglomerates also present. A description of the lithologies associated with each group is given in Table I.1.

Many brecciated, recessive weathering, and partly covered intervals are contained within the Starlight Evaporite and Vega Siltstone Members of the Whitehorse and Sulphur Mountain Formations (pers. comm. D.W. Gibson, April 1972). These characteristics generally indicate a poor degree of induration or cementation. Therefore these two members probably contribute the highest proportion of sediment to the surrounding streams, excluding the Pleistocene sediments.

The most significant erosion of the Starlight Evaporite and Vega Siltstone beds occurs in the very northern portion of the Bridge Creek catchment to the immediate east of the Middle Cambrian outcrop (Figure 1.3.) (pers. comm. D.W. Gibson, April 1972). Throughout the rest of the field area, the limestones, dolomites, quartzites, sandstones and pebble conglomerates are relatively resistant to erosion. This leaves only the shales and slate outcroppings as areas of very active scree development. These fine-grained rocks appear to be very susceptible to physical erosion and often break down to form clastic debris, fine enough for transportation by mudflow action.

1.2.3. Climate

In general, the area experiences a cold subhumid climate but specific characteristics are difficult to describe because of the lack of continuous data.

The nearest station operating all year is at Nordegg, 31 miles to the northeast and in the foothills. Records at this station (Table I.2.) show relatively high precipitation values, probably because of its exposure to the east. More typical of the field location are the climate

TABLE I.1.

GEOLOGICAL FORMATIONS AND LITHOLOGY, TWO O'CLOCK AND BRIDGE CREEK BASINS

Period	Group	Formation	Lithology	Described by
Jurassic	*	Fernie	Shale, limestone, fine sandstone.	Stott _et al_ (1968)
Triassic	Spray River	Whitehorse	Dolomitic sandstone, brecciated limestone, silty quartz sandstone, limestone.	Stott _et al_ (1968)
		Sulphur Mountain	Dolomitic siltstone, shale.	Stott _et al_ (1968)
Permeo-Pennsylvanian		Rocky Mountain	Sandstone, chert dolomite.	Irish (1965)
Mississippian	Rundle	**	Limestone, dolomite.	Oswald (1968)
Middle Cambrian	*	Stephen	Limestone, shale.	Aitken (1968)
		Cathedral	Limestone, dolomite.	Aitken (1968)
Lower Cambrian	Gog	**	Limestone, quartzite, minor shale.	Aitken (1968)
Proterozoic	Miette	Hector	Stable pebble conglomerate, limestone, purple slate.	Aitken (1968)
		Corral Creek	Slate, quartzite, pebble conglomerate, pebble grits.	Aitken (1968)

After Hirst (1971)

* No group name suggested.
** No formation name suggested.

TABLE I.2.

CLIMATIC DATA FOR SELECTED STATIONS WITHIN THE ROCKY MOUNTAINS, ALBERTA

Station	Elevation A.M.S.L. (feet)	Mean Ann. Temp. (F°)	Mean daily maximum and minimum temperatures (F°)												Precipitation (inches)	
			J	F	M	A	M	J	J	A	S	O	N	D	Mean Ann.	% as snow
Jasper	3480	37.3	21	29	38	50	61	67	74	70	63	51	34	26	16.0	30
			2	7	16	26	34	41	45	43	37	30	17	9		
Banff	4583	36.0	22	27	36	48	59	64	72	70	61	49	33	25	18.5	42
			3	6	14	25	33	39	43	41	36	29	17	9		
Nordegg	4300	33.8	20	26	33	45	56	62	69	66	59	49	34	24	21.7	38
			1	4	10	22	32	37	41	39	33	26	15	6		

Source: Temperature and Precipitation Tables for the Prairie Provinces
Canada - Department of Transport - Meteorological Branch, Toronto, 1967

stations at Jasper and Banff (Table I.2.). Both these sites are located in rainshadow areas within large river valleys protected from both the west and the east (pers. comm. R.W. Longley, April 1972).

From what information there is available, the field area also appears to be an area of locally unique arid climatic characteristics (Hirst, 1971). In 1954 the Eastern Rockies Forest Conservation Board set out a network of storage precipitation gauges in the headwaters of the North Saskatchewan River. The records for these gauges located near the field area are given in Table I.3. and the location of the gauges is shown in Figure 1.1. (Eastern Rockies Forest Conservation Board Management Report No. 2, 1968). The site on the fan near the study area (Gauge No. 2) shows the exceptional aridity of this location, a factor probably caused by the orographic effect of the Ram Range to the east (pers. comm. R.W. Longley, April 1972). Other gauges nearby are either at higher elevations or in valleys orientated east-west (Figure 1.1.). In a recent analysis of the soils of the area, Pettapiece (1971) constructed an isohytal map which he emphasizes "is partly conceptual" but is based on the values of the storage gauge records and other precipitation-altitude gradient records in alpine areas. He predicts that by an elevation of 6,000 feet A.M.S.L. the precipitation in the field area is in excess of 20 inches per year and by 7,000 feet it likely exceeds 25 inches per year. While these values are probably not accurate for any particular site, they do indicate the disparities in precipitation which may occur over short distances.

1.2.4. Vegetation

The field area is characterized by a vegetative climax of Engelmann Spruce (*Picea engelmanii*) or Engelmann - white spruce (*Picea glauca*) hybrids and alpine fir (*Abies lasiocarpa*) (Rowe, 1959).

Notable within the area is the disturbance of the forest cover by fire. The result of burning is the dominance of lodgepole pine (*Pinus contonta var. latifolia*). Only small areas of spruce-fir forest were noted and these can be detected in Plate 21 as the darker patches of vegetation within the forest cover. The majority of the forest consists of virtually pure stands of pine with lesser amounts of mixed pine-spruce stands. The extremely arid sites on exposed southwest facing slopes and

TABLE I.3.

STORAGE* PRECIPITATION GAUGE DATA FOR THE FIELD AREA

Gauge	Elevation	Years of record	Oct-May	May-Oct	Annual
1	4800	4	7.0	8.8	15.8
2	4400	10	3.7	7.4	11.1
3	5200	4	10.1	10.6	20.7
4	4500	8	9.0	7.2	16.2
5	5300	4	8.2	9.4	17.6

* Assume a 20% loss from evaporation. Precipitation in inches

Source: Eastern Rockies Forest Conservation Board Management Report No. 2 (1968)

ridges have very sparse tree growth although numerous stumps observed in the field indicate a denser stand in the past (see also Pettapiece, 1971).

Near the alpine zone and on the exposed ridges at higher elevations, a meadow type of vegetation is prevalent. Juniper is a dominant species (*Juniperus*) and cinquefoil (*Potentilla fruticosa*) is also present. In addition to grasses, several legumes and alpine herbs grow. The few trees and shrubs in these locations are stunted and often show signs of layering.

On the fan surfaces below the basins the dominant tree type is aspen (*Populus tremuloides*) and on the moist sites near the stream channels balsam poplar (*Populus balsamifera*) or spruce dominate.

1.2.5. Hydrology

Davis and Coulson (1967) subdivided the headwaters of the North Saskatchewan River into hydrologic zones based on mean monthly discharges. Bridge and Two O'Clock Creeks are in the Northern Mountain Zone which Davis and Coulson regard as a well defined zone having similar flow characteristics throughout.

Three streams are selected that drain within the Northern Mountain Zone and their flow characteristics are examined in general terms, to provide an introduction to the hydrological environment of the study area. These streams are Marmot Creek, Twin Creek and Ghost River and are located approximately 90 miles southeast of the study area. They are tributaries of the Bow and Kananaskis Rivers. The data for these streams are given in Table I.4.

All three streams show very similar runoff patterns. Flows are very low during the winter and early spring. They remain low until late May when significant increases in discharge usually start to occur. The major spring peak flow occurs within the last few days of May or in the first half of June. Throughout the early part and middle of summer, discharges remain relatively high with the continued possibility of additional peak discharges as a result of rainstorms and snow melt. By late July or August the flows decline again to near their winter values.

Monthly averages are not possible for the two years of records

TABLE I.4.

HYDROMETRIC DATA FOR SELECTED STREAMS WITHIN THE ROCKY MOUNTAINS, ALBERTA

Station	Station No. (Water Survey of Canada)	Drainage area square miles	Mean monthly and mean maximum monthly discharges (c.f.s.)												Years of record
			J	F	M	A	M	J	J	A	S	O	N	D	
Marmot Creek	5BF16	3.63	0.60	0.60	0.52	0.85	6.38	22.7	11.77	4.59	3.08	3.75	1.78	1.06	1965 -
			0.82	0.65	0.88	1.91	21.84	37.4	25.76	7.37	4.55	5.44	2.58	1.47	1968
Twin Creek	5BF18	1.02	0.26	0.21	0.18	0.19	1.61	8.66	4.53	1.53	1.03	1.23	0.57	0.38	1965 -
			0.30	0.29	0.25	0.33	6.95	15.37	7.30	1.81	1.43	1.62	0.81	0.44	1968
Ghost River	5BG2	80.50	-	-	-	20	75	508	320	197	144	92	50	-	1966 -
			-	-	-	36	369	1631	707	796	184	127	64	-	1967

Source: Surface Water of Alberta, Water Survey of Canada 1965-1968.

(1969, 1970) available for Two O'Clock Creek (McPherson, 1971a; McPherson, unpublished data, pers. comm. 1972) nor monthly values for the 1971 hydrograph record of Bridge Creek (Section 4.3.1.), because these data cover only two full months of the year. However observations of these daily discharge records show a very similar relationship to that discussed in the streams in Table I.4. In Bridge and Two O'Clock Creeks, discharges remained low until the end of May or early June when the spring peak flow occurred. A second major peak in each stream occurred later in the summer and during June and early July discharges remained relatively high. The discharges declined in late July and August with some exceptions due to heavy rainstorms.

1.3. Methods

The determination of bed-load transport has been attempted in many ways by other researchers, but these techniques fall into three principal categories:

a) Direct sampling

b) Estimations from bed-load formulae

c) Trapping bed-load by sedimentation.

All of these techniques were used in this study to determine a simple and reasonably accurate method of measuring or estimating bed-load transport in a mountain stream. Two other more recent techniques, that of tracer injection (Ramette and Heuzel, 1962; Hubbell and Sayre, 1964; Hollingshead, 1968) and acoustic instrumentation (see Hubbell, 1964; Hollingshead, 1968), have not been used. Bridge Creek was sampled with a small size, wire mesh basket sampler and the hydraulic characteristics of both streams were measured for use in the empirical equations which rely on water, sediment and channel variables to compute discharge of bed-load. In addition each stream was dammed with a low weir to trap the moving bed-load sediment in the pool behind.

Finally a reconnaissance was made of Bridge Creek catchment from field observations using aerial photographs to assist in the qualitative determination of possible sediment source areas. Bridge Creek catchment was selected from aerial photographs because it appeared to have more areas of accelerated erosion near the stream channel.

Special attention was given to the supply of sediment to the stream channels and how this supply would fluctuate throughout the season. As a result, a relationship between the geomorphic processes within the basin and the sediment transport characteristics has been tentatively formulated.

CHAPTER II

THEORY

2.1. Sediment Load

The total sediment load is the mass rate of discharge of solid materials transported by the stream. This is usually artificially subdivided into categories which are commonly defined as follows (Einstein, 1950):

Washload refers to the very small sediment particles transported by the flow which are not found in significant quantities in the stream bed.

Bed material load refers to the sediment particles transported by the flow which are found in significant quantities in the stream bed.

Suspended load refers to the sediment particles which are suspended in the flow turbulence.

Bed-load refers to the sediment particles which are too heavy to be suspended by the turbulent action of the flow. These particles move by rolling, sliding or saltating along the stream bed.

It would appear from this classification that bed-load is easily defined; however there are many problems associated with the measurement of bed-load in the field. Firstly, depending on the flow conditions at the time of measurement, sediment may at one time be suspended load and at another time be bed-load. Secondly, the elevation above any particular point on the channel bed at which bed-load becomes suspended load is difficult to define for bed-load measuring purposes. Consequently small errors committed in estimating the separation level between the bed-load and suspended load can have large scale effects on the measured bed-load rate (Stein, 1968).

In this study it is assumed that there is a sufficient drop in velocity behind both weirs to prevent the continued passage of rolling, sliding or saltating bed-load particles and that any material carried through the pool is in suspension. It is also assumed that any material

caught in the bed-load sampler is bed-load. It is possible that a certain amount of suspended material would settle out in the pools, particularly at moderate discharges. Because of a loss of data during the laboratory analysis, it was not possible to compare the mechanical analysis of the suspended load with the finer material caught in the weir. For this reason it must be stressed that the amount of material caught in the weirs, while the best possible estimation of bed-load available under the circumstances, is probably an over-estimation due to the presence of some suspended material that has settled out with the decrease in velocity.

2.2. Sedimentation

Several bed-load measuring techniques have been developed involving sedimentation. Muhlhofer trapped bed-load sediment with a number of pit samplers, the top of which were flush with the channel bed (Federal Interagency River Basin Committee, 1940). Other more elaborate structures continuously withdraw and weigh bed-load after it falls into a slot or pit in the stream bed (Federal Interagency River Basin Committee, 1940; Einstein, 1944; Milhous and Klingeman, 1971). A similar technique to that used in this study is the determination of bed-load discharge by measuring the time required for a pit of known volume, excavated in the stream bed, to fill with sediment (Hollingshead, 1968).

Brown, Hansen and Champagne (1970) developed an accurate system for measuring total sediment discharge from small watersheds in Arizona. It consists of a concrete weir with a reservoir behind it which catches the coarse sediment load. This is emptied periodically and the sediment weighed or the volume estimated, depending on the amount caught. In addition, there are a series of water-sediment splitters within the weir structure. These collect (by repeatedly dividing part of the stream flow into smaller and smaller portions) a representatively split sample of water and suspended sediment mixture for the determination of suspended sediment load. However, care must be taken to prevent the reservoir filling with sediment as the splitters are not capable of handling the coarser bed-load grain sizes.

Milhous and Klingeman (1971) have utilised a particularly

sensitive technique for measuring even minor fluctuations in bed-load discharge. The design is based on a vortex tube sand trap for excluding sediment from canals. It consists of a vortex flume constructed diagonally across the channel bed. A vortex of flow along the flume removes bed-load, along with a small fraction of the total stream flow, to an off channel trap where the sediment is collected and weighed.

While sedimentation techniques are also subject to error in the estimation of bed-load transport, it is assumed in this study to be the most accurate technique. The time and expense that have gone into recent sedimentation studies of bed-load transport (Brown, Hansen and Champagne, 1970; Milhous and Klingemann, 1971; McPherson, 1971a) suggest that this technique is regarded as more accurate than the simpler direct sampling methods using portable samplers. For this reason the relatively simple yet effective method of measuring the rate of accumulation of sediment behind a weir was selected (McPherson, 1971a). While this technique is not as sensitive to fluctuations of bed-load during time as many of the sampling or continuous withdrawal methods are, the result for each survey approaches an absolute value.

2.3. Direct Bed-load Sampling

The simplest method of measuring bed-load discharge is to use a portable sampler. There are, however, inherent difficulties in this technique. Because the sampler represents an obstruction to flow, it disrupts the flow pattern and the bed-load transport pattern near the sampler. Also, as the sampler fills with sediment, it acts as more of an obstruction to flow than when empty and its rate of filling will change. It is evident that for accurate bed-load discharge measurements, the sampler must be designed so that the flow conditions near the bed are virtually unaltered. It is also desirable if the sampler can sample all grain sizes and orientate itself to the direction of flow. These problems of measurement cannot be overcome by the bed-load samplers presently in use and therefore each sampler type must be calibrated for the set of conditions in which it is being used. Taking these limitations into account, the most useful sampler is one that has a constant error, for once this error has been established, it can then be accurately accounted for.

Hubbell (1964) reviews the apparatus and techniques for measur-

ing bed-load. He considers the factors that contribute most to inaccuracies in sampling. The oscillating variation in bed-load discharge shown by Ehenberger (1931) and Einstein (1937) is the most severe source of error. These oscillations show very marked variations of up to ten times within a few minutes. A satisfactory means of overcoming this problem is to take a sufficient number of samples during each sampling period, and thus find an average transport rate (Hubbell, 1964).

For this study, a basket sampler was selected. On the basis of work done by Hollingshead (pers. comm.) it appeared to be the sampler type with the most constant efficiency factor, although it is not necessarily the highest. A small sized basket sampler was selected for ease of handling in such a small stream. The sediment sampled in Bridge Creek was coarse-grained and thus suitable for collecting in a quarter inch wire mesh basket.

In his review, Hubbell states that the average efficiency of the basket sampler is 45 per cent. Evidence from the present study and from work currently being undertaken in the Hydraulics Laboratory at the University of Alberta (pers. comm. Charles Gibbs, 1972) suggested that a range of 50 per cent at high discharges to 30 per cent at low discharges would be more realistic.

2.4. Estimation of Bed-load Discharge by Formulae

The relationships that exist between the flow of water in a river and the mobile boundary are complex in detail and even in ideal situations they are not fully understood. However, this has not prevented numerous attempts to devise empirical relationships between the variables and thus attempt a prediction of the bed-load capable of being transported. These predictions are necessary because of the extreme difficulty of measuring bed-load transport in rivers of any size.

The first of these relationships was proposed by du Boys in 1879 (see Leliavsky, 1966) and is based on a tractive force criteria. Here the transport rate depends on bed shear, critical bed shear, slope and sediment size.

$$q_s = M \tau o \ (\tau o - \tau c)$$

Where: q_s = volumetric rate of sediment transport

τo = tractive force at a given depth of flow

τc = critical tractive force at the threshold of motion

M = material parameter which is a function of the slope and the particle size

This resulted in a group of equations known as the tractive force formulae, an example being that of Shield's (1936):

$$g_s = \frac{10qS\gamma f}{(\gamma s - \gamma f)\ \gamma s\ d} \ (\tau o - \tau c)$$

Where: g_s = rate of sediment transport by weight per unit width

d = grain size

q = water discharge per unit width

$(\tau o - \tau c)$ = same as for du Boys' equation

S = bed slope

γf = specific weight of water

γs = specific weight of sediment

Later workers used the close relationship between discharge and bed-load, above a critical discharge, to determine bed-load transport. Laursen (1957) and Rottener (1959) based their work on the relationship between bed-load discharge (G_s) and relative roughness (D/H) where D = grain size and H = depth of flow. Blench and Erb (1957) describe a technique for determining bed-load transport based on regime theory derived from the interrelation of self-adjusting variables in canals.

Shulits and Hill (1968) have published a very comprehensive review of bed-load formulae and recognise that the selection of a bed-load formula for a particular range of field conditions is a problem. As yet there is no universal bed-load formula and no best or more accurate one to use under a wide range of conditions. They therefore recommend that it is prudent to resort to a few well-known selected formulae and to try these under a variety of field situations. A problem with this suggestion is that it assumes that the formulae which they suggest fall within the experimental range of any particular field situation requiring study.

The three formulae that Shulits and Hill suggest are the Meyer-Peter and Muller (1948) formula, the Straub (1935) formula, as these represent the tractive force group of formulae, and the Schoklitsch (1934) formula as a discharge based formula. They do not imply that these equations are more accurate than any other, but that they merely agree more closely with the other formulae that they represent in their group.

These equations can be applied in a great variety of field conditions, such that coefficients and exponents may be obtained although these may be only valid for particular fluvio-geomorphic regions. "Turbulence research, being intrinsically so difficult and so time consuming, it is presently prudent to resort to a few selected and existing bed-load formulae" (Shulits and Hill, 1968, p. 7). However this method of adjustment will not improve the relationship unless the shape of the calculated bed-load rating curve roughly parallels that determined in the field.

The fact that these joint authors have made no attempt to relate any of the formulae that they examine to actual field examples, reflects the lack of accurate bed-load data on which to base such an analysis. They state that "if it is sought, most likely a field proof of any formula could be found ... which would only be more confusing" (loc. cit.).

Several "proofs" have been found for a number of formulae and the combined result is that no uniform pattern emerges. Stall et al (1958) gives evidence for the accuracy of the Schoklitsch (1934) formula as a result of reservoir surveys in Illinois. Alternatively Richter (1964) found that the Schoklitsch (1943) formula agrees satisfactorily with measurements of degradation below dams in Austria. In contrast, Burz (1956) finds from sediment accumulations measured by reservoir and delta surveys in Bavaria that the Meyer-Peter and Muller (1948) formula agrees best. Hansen (1966) also supports this formula from measurements made with a bed-load sampler and from dune migration (see Shulits and Hill, 1968).

The Task Committee for the Preparation of Sediment Manual, Committee on Sedimentation of Hydraulics Division (1971) examined thirteen

well-known bed-load formulae in a study to find the most accurate formulae presently in use. Using total sediment discharge data from the Colorado River and the Niobrara River (sand bed rivers), they found that the Colby (1964) relation, Tofaletti (1969) formula and the Engelund-Hansen (1967) relation to be the most accurate. However the committee recommends that if suspended-load sampling is undertaken, then unmeasured bed-load discharge should be based on a Modified Einstein method to obtain the most accurate method of total discharge determination.

Hollingshead (1971) found that the Modified Einstein (Colby and Hubbell, 1961) technique gave the most accurate result of the three formulae that he tested in the Elbow River, a gravel bed river in the foothills of the Rocky Mountains, Alberta. In addition, Hollingshead obtained a very satisfactory relationship with the Cooper (1970) analysis which is particularly simple to apply. This latter procedure, however, requires accurate measurements of velocity at several representative cross sections and instrumentation for determining the width of mobile bed at these sites

As a result of a review of recent literature pertaining to bed-load formulae, it was decided to apply four of the more commonly known equations to the two alpine streams under study.
These are:

1) the Meyer-Peter and Muller (1948) equation

2) the Schoklitsch (1934) equation

3) the Blench (1969) regime equation

4) the Modified Einstein (Colby and Hubbell, 1961) equation.

Shulits and Hill (1968) recommend the Meyer-Peter and Muller (1948) equation and the Schoklitsch (1934) equation as representing the tractive force formulae and the discharge formulae respectively. The Meyer-Peter and Muller (1948) equation has been developed for slopes between 0.006 and 0.030 and grain diameters of 0.1 to 1.2 inches. The conditions in the study area are slightly beyond the upper extent of these conditions, but this formula has the closest experimental range of any of the four formulae used.

The Schoklitsch (1934) formula has been developed under

experimental conditions of slopes between 0.004 and 0.030 and grain sizes between 0.1 and 0.3 inches.

The Blench (1969) regime slope equation is used as it has been developed from the Gilbert (1914) data with grain sizes ranging up to 0.3 inches. In addition Blench has had experience with the determination of bed-load in gravel rivers.

Because of its wide acceptance and reports of considerable accuracy for a number of field locations including gravel bed rivers, the Modified Einstein equation (Colby and Hubbell, 1961) is applied. All four equations are used with considerable trepidation, however, as it is fully realized that the conditions in such rough boundary, steep, shallow mountain streams are not the conditions the formulae were derived for. Considerable variations in water temperature, bed armouring, rising and falling stage and possible changes in the supply of sediment to the stream may also effect the predictive accuracy of these equations.

2.4.1. Meyer-Peter and Muller Equation (1948)

The Meyer-Peter and Muller equation is the most commonly used bed-load formula of its kind. It can be written as:

$$0.25\rho^{1/3}\, g'_s{}^{2/3} = \gamma_f\, RS\left[\frac{Kb}{Kg}\right]^{3/2} - 0.047\, \gamma_s\, D_E$$

Where:

ρ = mass density of the fluid

g'_s = sediment discharge per unit width, (submerged weight)

γ_f = specific weight of fluid

R = hydraulic radius of channel cross section

S = channel slope

γ_s = specific weight of sediment

D_E = effective grain size diameter

Kb = Strickler roughness coefficient

Kg = particle or grain roughness

The bed roughness (Kb) is the total bed roughness due to both grain size roughness and that due to bed form resistance.

The particle or grain roughness (Kg) is defined as $Kg \doteq 26/D_{90}^{1/6}$ where D_{90} is in meters. This is a measure of the resistance due to grain

size only and is strictly applicable to only fully turbulent conditions. In English units

$$Kg = \frac{48}{D_{90}^{1/6}} = \frac{1.49}{n'}$$

Where: $n' = 0.031\ D_{90}^{1/6}$

The Strickler roughness coefficient (Kb) is determined from the Manning formula:

$$Vm = \frac{1.49}{n}\ R^{2/3}\ S^{1/2} \quad \text{(English units)}$$

Where: $Kb = \frac{1.49}{n}$

therefore $Kb = \frac{Vm}{R^{2/3}\ S^{1/2}}$

The symbols have the same definition as for the Meyer-Peter and Muller equation above.

$\left[\frac{Kb}{Kg}\right]^{3/2}$ is a reducing factor which determines in the presence of form resistance what part of the total available tractive force (Υ.R.S.) is available for bed-load transport. Since only Kg will effect the actual entrainment of materials, this is an important distinction.

The term $\frac{Q_B}{Q}$ which occurs in the original form of the Meyer-Peter and Muller equation, is not used here. This factor accounts for the fact that only a part of the discharge acts on the bed. Because it is assumed that these streams lose very little of their hydraulic radius to the side walls, $\frac{Q_B}{Q} \simeq 1$.

The effective diameter D_E is the mean diameter by weight.

$$D_E = \frac{\Sigma D\ \Delta p}{100}$$

where D is the average size of particles in a particular size fraction and Δp is the percentage of that size fraction of the total weight.

2.4.2. Schoklitsch (1934) Formula

This formula can be termed a discharge formula for it has been assumed that a certain discharge Q_{01}, will represent the critical tractive force at which bed-load will be on the verge of moving. Any discharge above that point will therefore contribute to the movement of bed-load.

For determining this critical tractive force, Schoklitsch used the relationship

$$Q_{01} = \frac{0.0001944\ D_E}{S^{4/3}}$$

where D_E = effective grain size and the specific gravity of the sediment is 2.66.

This formula is based on visual observations in a flume and according to Shulits and Hill (1968) the formula is highly unreliable. For this reason it was decided to use visual observations and basket sampling measurements in the field to determine critical discharge.

In English units the formula is written

$$G_1 = 25 \frac{S^{3/2}}{D_E^{1/2}} (Q_1 - Q_{01})$$

for bed-load in lbs./sec./ft.

Where: G_1 = bed-load/foot width/sec., dry weight
S = slope
D_E = effective grain size
Q_1 = discharge/foot width
Q_{01} = critical discharge in c.f.s./foot width

To determine the effective grain diameter, the bed-load sediment mixture is considered to be made up of a number of grades of mean diameter (D_a, D_b, D_c,....). The divisions between these are arbitrary but the percentage of each grade of sediment is noted (a, b, c,....). The formula is then applied using the mean of each sediment grade for the D_E value. The slope and discharge are held constant. The results of bed-load charge for each grade of sediment, corrected for the percentage of the total that each represents, are then added together. ($G_1 = \frac{a}{100} G_{1a} + \frac{b}{100} G_{1b} + \frac{c}{100} G_{1c}$). Once the bed-load discharge has been determined for the slope and water discharge selected, the Schoklitsch equation is calculated to find which effective grain diameter (D_E) yields the same load.

2.4.3. Blench's Regime Slope Equation

The regime theory (see Blench, 1969) on which this equation is based, evolved among engineers who constructed and maintained irrigation canals in India at the end of the nineteenth century. Briefly outlined, the regime formulae were derived by studying the interrelationships between depth, breadth, and slope of canals that had adjusted to equilibrium conditions despite the repeated efforts of engineers to make them run unnaturally. After their self-adjustment, these canals were

considered to be "in regime".

Blench (1955) and Blench and Erb (1957) have employed the regime theory in the analysis of Gilbert's (1914) flume data involving bed-load transport. Gilbert's data incorporate bed material from medium sand to medium gravel (0.3 inches) and are probably the most exhaustive laboratory flume tests on record. This analysis of the data using the regime equations resulted in the regime formulae for bed-load transport.

Blench (1969) recommends the use of the regime equations to determine the bed-load charge in the form:

$$f'''_{(c)} = \frac{S\ K\ b^{1/6}\ Q^{1/12}}{k\ F_{bo}^{\ 11/12}} \qquad \text{where} \qquad K = \frac{3.63g}{\nu^{1/4}}$$

$$f'''_{(c)} = \frac{(1.0 \times 12c)^{11/12}}{1 + c/222}$$

and is given by Blench (1969, Figure 7.2.).

k = the meander correction coefficient and varies from 1.25 to 2.75 for natural rivers

$F_{bo} = 7.3\ {}_{w}^{m}D_f^{\ 1/4}\ (\frac{\nu_{70}}{\nu})^{1/6}$, for $\frac{d}{D} > 50$

${}_{w}^{m}D$ = mean grain size by weight

ν = Kinematic viscosity of the fluid

ν_{70} = Kinematic viscosity of the fluid at 70°F

d = mean depth

D = the particle diameter D_{50} in feet by weight

Because the regime equations were developed for straight sand bed canals, Blench has introduced the correction coefficient (k) for natural rivers. This takes into account that portion of the energy slope dissipated through curvature of flow and by irregular bed forms. For natural rivers, the value of k varies from 1.25 to 2.75.

In determining zero bed factor, Blench recommends the formula

$$F_{bo} = 7.3\ {}_{w}^{m}D_f^{\ 1/4}\ (\frac{\nu_{70}}{\nu})^{1/6}$$

However the author warns that this formula should not be used in gravel rivers unless d/D exceeds 50. For this reason it was decided to obtain an estimate of F_{bo} from the relation $F_b = \frac{Vm^2}{d}$ at conditions where the bed-load charge is known to be nearly zero.

Vm = mean velocity

$F_{bo} \approx F_b$ when bed-load charge is nearly zero (Blench, 1969)

2.4.4. Modified Einstein Procedure described by Colby and Hubbell (1961)

Einstein (1950) presented a procedure for computing total discharge of sediment sizes found in appreciable quantities in the stream bed. Computations are made for several sizes and involve many variables, thus resulting in a series of complex calculations.

Because of the many variables used, and the detailed analysis made in its formation, the Einstein equation is one of the most widely used and "trusted" bed-load equations. However a study of the original presentation is a tremendous task in itself and as a result, Colby and Hembree (1955), Schroder and Hembree (1956) and Colby and Hubbell (1961) have devised simplified techniques for solving the original equations. Colby and Hubbell's technique uses a graphical approach in solving the relationships, employing a series of nomographs. These can be applied without an extensive knowledge of the fluid mechanics involved in the original theory.

The first step in computing sediment discharge using the Modified Einstein procedure is the solution of $\sqrt{(RS)m}$ by trial and error from Plate 1 (Colby and Hubbell, 1961) using known values of mean velocity (Vm) and depth (d) in the equation:

$$Vm = 5.75 \sqrt{g(RS)m} \log_{10} \left(12.75 \frac{xd}{k_s}\right)$$

Vm = mean velocity

g = gravity constant

$(RS)m$ = product of the hydraulic radius and the energy gradient as computed by solving the equation using a known mean velocity

d = average depth

x = dimensionless parameter to be determined from Plate 1 (Colby and Hubbell, 1961)

k_s = the roughness diameter. That particle size of bed material for which 65% by weight is finer.

All quantities are expressed in foot-pound-second units.

The bed material is divided into several size ranges and the shear on the sediment particles (Ψm) is determined for each size range using the equations:

$$\Psi_m = (Ss - 1)\ D_{35}\ /(RS)_m$$

or

$$\Psi_m = (Ss - 1)\ 0.4\ Dg/(RS)_m$$

whichever would yield the greater Ψ_m.

Dg = the geometric mean of the size fraction

Ss = specific gravity of the solid sediment particles

According to the modified relationship the intensity of bed-load transport (Φ*) is $\Phi*/2$, if Φ* is determined from the relationship between Φ* and Ψ* (Einstein, 1950) by substituting Ψm for Ψ*. These values of Ψm are therefore used as Ψ* in the $\Psi*-\Phi*$ function of Einstein, to obtain values of the intensity of bed-load transport (Φ*). The bed-load discharge can then be calculated for each size range using the equation

$$ib\ G_s = p\ 43.2 \times 1200 \times Dg^{3/2} \times 1.39 \times \frac{\Phi*}{2}$$

$$= i_b \times b_w \times Dg^{3/2}\ \Phi* \times 36000$$

and then the values of $i_b\ G_s$ are summed to give a total G_s for a particular water discharge.

ib = fraction of the bed material in that size range

p = wetted perimeter

1.39 = the conversion factor from tons/day to lbs./min.

2.4.5. Conclusion

These selected formulae represent a wide range of theoretical concepts that are considered significant for the transport of bed-load. They are applied in this particular situation in the hope that one or more of them will relate with reasonable accuracy to the measured bed-load transport rating curve. Should this happen it will not necessarily mean that a formula has been found for use in small steep alpine streams. Further testing in similar physiographic areas would be required, as the

result of this survey could be coincidental with the streams under study and not representative of a range of alpine streams.

CHAPTER III

FIELD AND LABORATORY TECHNIQUES

3.1. Introduction

The methods used in this study are readily available to field workers in fluvial geomorphology and in some cases are adaptations of ideas used commonly by river engineers studying larger rivers. On the basis of the techniques used in this project, it is hoped that a suitably accurate method for measuring bed-load in small alpine streams might be determined. A number of difficulties were incurred because of lack of experience and in some cases the need for more assistance to enable efficient operation. However, despite these difficulties, useful results were obtained and these may assist others in planning and carrying out similar studies in small streams.

3.2. Climatic Data

A thermohydrograph was located at the base camp on Two O'Clock Creek fan and a continuous record of temperature was obtained from early May to late July. Rainfall was measured daily, using a rain gauge located at the weir site on Bridge Creek. These instruments gave an index of temperature and rainfall in the catchments but a more intense instrument network would be required within the basins' 4,500 feet of relative relief to give a meaningful coverage of climatic conditions.

3.3. Velocity and Discharge Measurements

Velocity was measured using an Ott current meter at a selected site on each stream (Figure 1.2.). Discharge was determined from measurements of the cross section each time velocity was measured. These results were then related to steel staff gauges hammered into the bed of each stream at their respective discharge sites.

A continuously recording Ott water level recorder was used with an 18 inch diameter pipe stilling well on Bridge Creek (Plate 8). No such recorder was available for Two O'Clock Creek so readings of water level were taken from the staff gauge at the discharge site. During high

flow periods up to four readings were taken per day and these were related to continuous water level recorder charts taken on Two O'Clock Creek in 1970 (pers. comm. H.J. McPherson, 1972). This gave the correct shape for the daily hydrograph and ensured a reasonably accurate measure of discharge at high bed-load discharge periods. Because daily discharge variations from Two O'Clock Creek basin were observed to be controlled almost wholly by diurnal temperature fluctuations during the study period, the daily water level fluctuations took on a regular diurnal pattern. It was found from observations in the field and from previous continuous recordings that peak diurnal flows on Two O'Clock Creek occurred between 1900 and 2000 hours and that the lowest daily flows occurred between 1000 and 1200 hours.

During the high flow days, the weir on Two O'Clock Creek required almost constant daytime attention. As a result, maximum and minimum flows for each day could be accurately recorded during this time. Even at low flows a close watch was kept on water level as the creek was within a few hundred yards of the base camp.

It is assumed that except for minor fluctuations during low flow periods, an accurate assessment of discharge has been made.

3.4. Channel Geometry

Five cross sections were selected on each stream in addition to the already chosen discharge sites. These were positioned at 200 foot intervals above Bridge Creek weir and at 200 foot intervals below the Two O'Clock Creek weir. Cross sections were then measured at various discharges using a tape measure and a calibrated steel rod. The latter was used to take depth measurements at at least 10 regularly spaced intervals across each section. The results of these measurements were then used to construct graphs of channel geometry providing relationship with discharge (Q) of mean depth (d) and mean width (w). Mean velocity (v) was determined from these three variables on the basis of the relationship:

$$v = \frac{Q}{dw}$$

These values of average depth, velocity and width were determined for

use in the empirical bed-load formulae.

3.5. Suspended Load Sampling and Analysis

Water samples were collected at the Bridge Creek discharge site with a U.S.G.S. DH 48 depth integrating sampler by wading and sampling in the centre of the stream. Up to four samples were taken per day depending on the flow conditions and towards the end of the season, sample times became very intermittent as the stream remained clear most of the time. All samples were stored in sealed jars until the end of the field season when they were taken to the laboratory in the Geography Department at the University of Alberta for analysis.

The volume of each water sample was measured using a 500 ml measuring cylinder. They were then filtered through Whatman No. 2 filter papers using a vacuum flask and funnel. The filter papers were ashed at between 400° and 500° C in a furnace for one hour and the residue weighed to the nearest 0.0005 gm on a Mettler balance. For additional strength while vacuum filtering, two filter papers were used for each sample and an average ash weight of these two filter papers was determined at 0.0045 gm.

3.6. Weir Sedimentation Method

The construction of weirs specifically for the purpose of measuring bed-load transport is unique to the study of small mountain streams (Brown, Hansen and Champagne, 1970; McPherson, 1971) and it is closely related to other sedimentation processes such as pit sampling. Weirs were constructed of logs and boulders across both Two O'Clock Creek and Bridge Creek (Plates 5, 6 and 7). The Bridge Creek weir was built largely of spruce trunks laid across the stream and stayed in place with shorter lengths of timber. Quarter inch chicken wire was then tacked over the log structure on the upstream side to ensure the trapping of leaf litter floating down the stream, making the weir more sediment proof. The structure stood nearly 5.5 feet high over the thalweg of the channel and was 20 feet in width.

Two strongly supported wires were then stretched for 50 feet on the sides of the reservoir upstream from each end of the weir. At every two feet along the wires, a nylon cord was stretched across the

pool and these cords marked at every 2 feet. This gave a grid network with each point representing approximately 4 square feet. A total of 430 points covered the reservoir area of 1679.4 square feet (Figure 3.1.).

At intervals during the runoff season the ground elevation directly below each grid point was surveyed using a theodolite and staff such that for each set of readings, an average elevation for the floor of the reservoir could be determined. By subtracting each average reading from the previous survey reading, the volume accumulation of sediment over the bed of the reservoir was determined.

Similarly a weir was constructed across Two O'Clock Creek using the same site as that used in 1969 by McPherson (1971). In this case the weir was 4.5 feet high and the grid network extended upstream for 25 feet (Figure 3.2.). The slope of the channel was 0.114 which is considerably steeper than for the weir site on Bridge Creek (0.067). In both cases, however, adequate provision was made for the backwater effect. At intervals during the infilling, sediment was shovelled by hand out of the front of the Two O'Clock Creek reservoir and the new level resurveyed. The total number of points behind the Two O'Clock Creek weir was 234 and again, each point represents approximately 4 square feet. The total area of the reservoir was 936 square feet.

After the weirs had half-filled with sediment, only the survey points at the front of each weir were used. This could be justified because the deltas that built out on to each weir had very flat upper surfaces with very little relative relief and most of the volume change occurred between the weir and the leading edge of the delta.

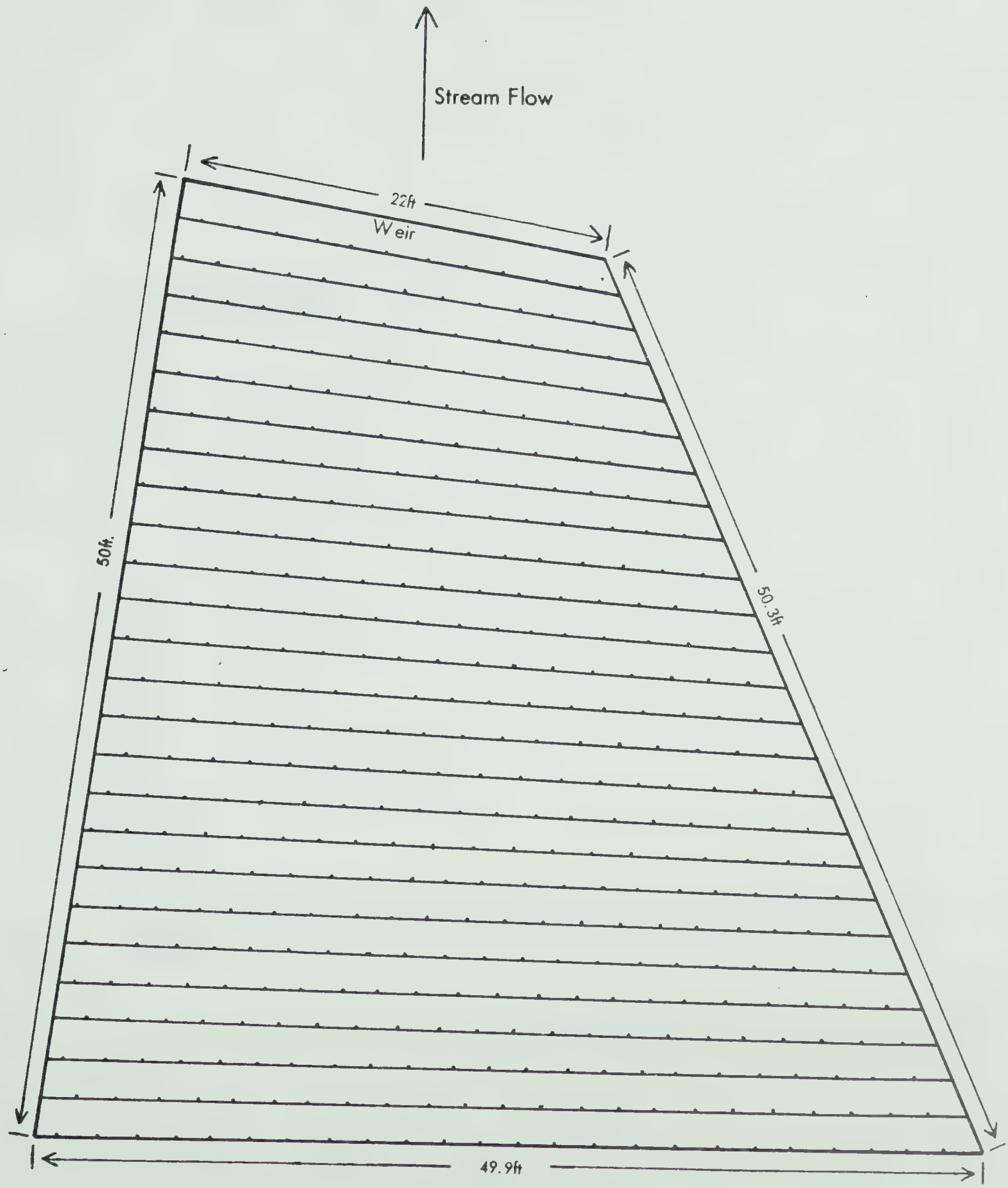
3.7. Basket Sampler Method

The basket sampler consists of a rectangular pipe frame into which fits a basket with one end open. The basket size used was 15 inches long, 12 inches wide and 6 inches deep and the whole sampler weighed 80 pounds. The smallest mesh sizes available were used, consisting of half inch mesh on the top of the basket, quarter inch mesh on the sides and back and 3/16 inch on the bottom. Behind the frame holding the basket there is a three finned tail section that keeps the open mouth of the sampler pointing up stream (Plate 10).

FIGURE 3.1

PLAN OF BRIDGE CREEK POOL SHOWING SURVEY POINTS

SUMMER 1971



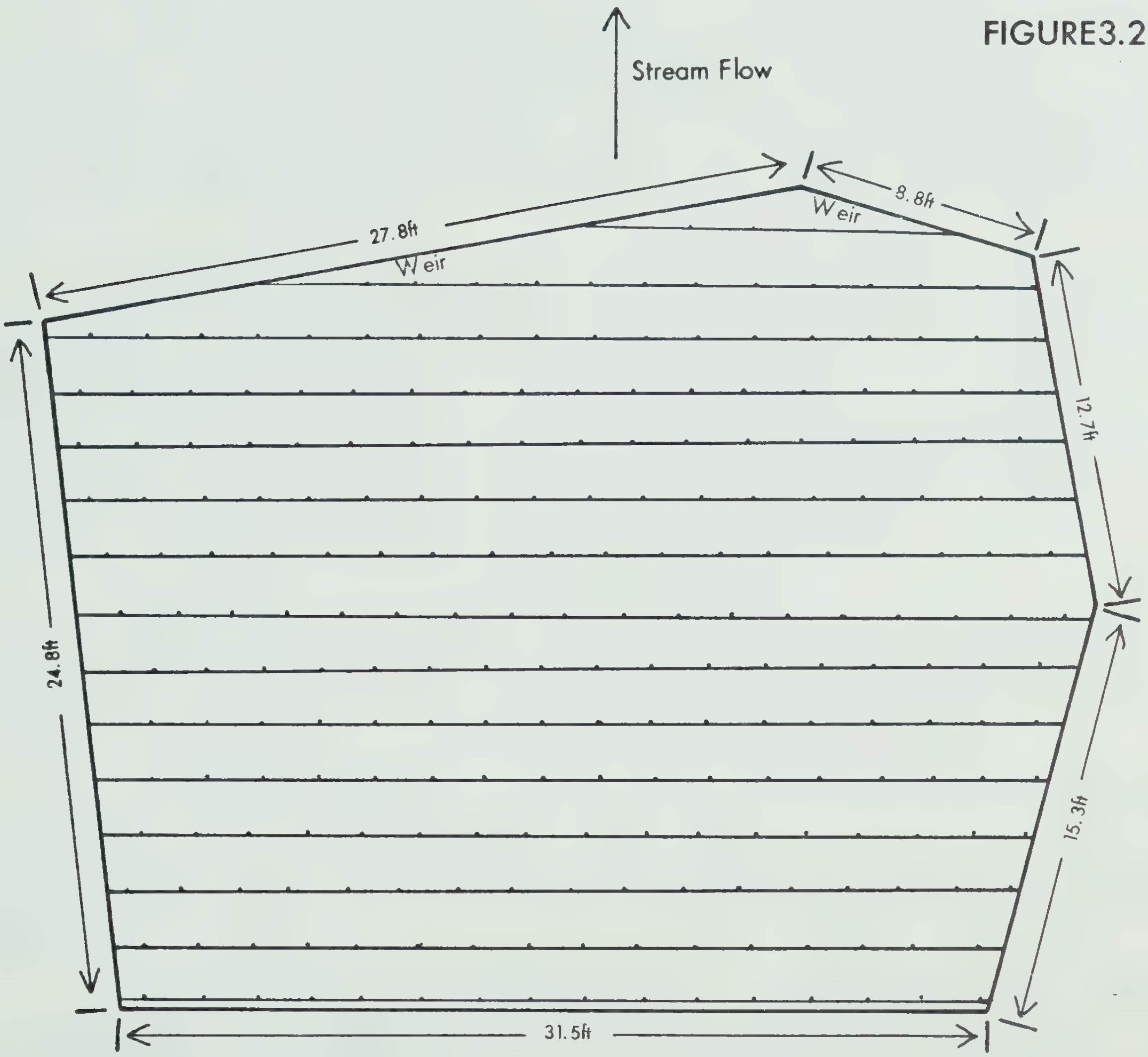
Area 1679.4 square feet

430 points

PLAN OF TWO O'CLOCK CREEK POOL

SHOWING SURVEY POINTS SUMMER 1971

FIGURE3.2



Area 936 square feet

234 points

The raising and lowering of the sampler was accomplished with the use of a half ton chain winch suspended over the stream on a rigid derrick (Plate 9). After the loaded sampler was lifted clear of the stream it was pulled to the bank by one operator as the other worked the winch to bring it to rest on the bank. The contents of the sampler were weighed separately and returned to the stream or a portion kept for sieve analysis.

A log sill was constructed at low flow to ensure a good fit between the base of the sampler and the bed of the stream. Heavy boulders were placed on either side of the log sill to hold it in place and to direct the water and sediment flow through the confined sampling site.

Samples were taken at three locations across the 7.5 foot log sill: left bank, mid stream and right bank. Because of the weight of the sampler it was not necessary to stay the front of it in position, but one operator had to stand in the stream to ensure that the sampler was securely seated. Sampling times varied depending on the rate of sampler filling which was determined by trial and error.

Difficulties were experienced at higher flows in handling the sampler and probably rigid stay wires would be required at flows higher than 40 c.f.s.

To prevent spillage of sediment out of the mouth of the sampler while it was being raised, the basket was slung under the winch such that when the winch was raised, the nose of the sampler came away from the bed before the tail section.

Basket sampling was undertaken only on Bridge Creek because of the difficulty of transporting the 80 pound sampler and accompanying winch. Also because bed-load moves on only a relatively few days a year, it was thought best to obtain as many samples as possible on the one stream.

3.8. Measurements of Bed-load Grain Size

Bed-load grain size for use in the empirical bed-load formulae was obtained with three pit sieve samples from the sediment behind each weir. In addition one sample was taken from the bed material in Bridge

Creek 50 yards above the furthest extent of the reservoir from material on a point-bar that had recently been covered by flood water.

The samples were taken on different occasions throughout the field season and were sieved using 4 inch, 2 inch, 1 inch, 3/4 inch, 1/2 inch and 3/8 inch mesh field sieves. Samples of material less than 1 inch were washed, reweighed to determine what percentage of their previous weight was contributed to by finer particles adhering to their surfaces. In addition a sample of the sizes less than 1 inch was weighed wet, sealed and then dried in the laboratory to determine what percentage of its weight was the result of there being water adhering to the grains. For material 1 inch or larger this was not considered necessary.

In the case of each sample weighed in the field, the "b" or intermediate axis and the weight of the largest particle was recorded so that the probability grain size curves could be completed for the largest sizes. From the material less than 3/8 of an inch, a sample was collected and returned to the laboratory for fine sieving. Material finer than 0.063 mm was analysed by pipette analysis.

In addition one sample each of the till, fluvio-glacial deposits and colluvium found in the catchment in the steep stream cut banks, were sieved in the field. Material less than 3/8 inch was returned to the laboratory for fine sieving and pipette analysis.

CHAPTER IV

OBSERVATIONS AND ANALYSIS OF HYDRAULIC VARIABLES

4.1. Introduction

In 1969 and 1970 water discharge and sediment data were collected during the spring and summer for Two O'Clock Creek (McPherson, 1971a; McPherson, unpublished, pers. comm. 1972). As a result, it was thought desirable to study an adjacent alpine stream for which no previous data had been collected.

Observations were started on Bridge Creek on the 14th May, 1971 and continued until the 28th July, 1971, although a continuous water level recorder was operated until the 26th August of that year. An interruption occurred when the weir constructed to trap bed-load in Bridge Creek burst after a heavy rainstorm on the 5th June. As a result the study was extended to Two O'Clock Creek from the 18th June to the 25th July to obtain complementary bed-load data.

4.2. Water Discharge

The techniques for measuring and estimating water discharge in both streams are discussed in Section 3.3.

From measurements of water discharge (Table IV.1.) a stage height discharge rating curve is constructed for Two O'Clock Creek (Figure 4.1.). This rating curve is used to relate the numerous stage height readings made in Two O'Clock Creek throughout the study period (Table IV.2.) to actual water discharge.

Using the 1970 continuous water level recorder chart for Two O'Clock Creek (pers. comm. McPherson, 1972) and from observations made during the study period, it was noted that peak diurnal flows on Two O'Clock Creek occurred between 1800 and 2000 hours and that the lowest daily flows occurred between 1000 and 1200 hours. These regular fluctuations persisted as long as discharge was controlled by diurnal snow melt and not rainfall. During the time that Two O'Clock Creek was studied, rainfall was not observed to disrupt this diurnal pattern.

DISCHARGE RATING CURVE TWO O'CLOCK CREEK

FIGURE 4.1

SUMMER 1971

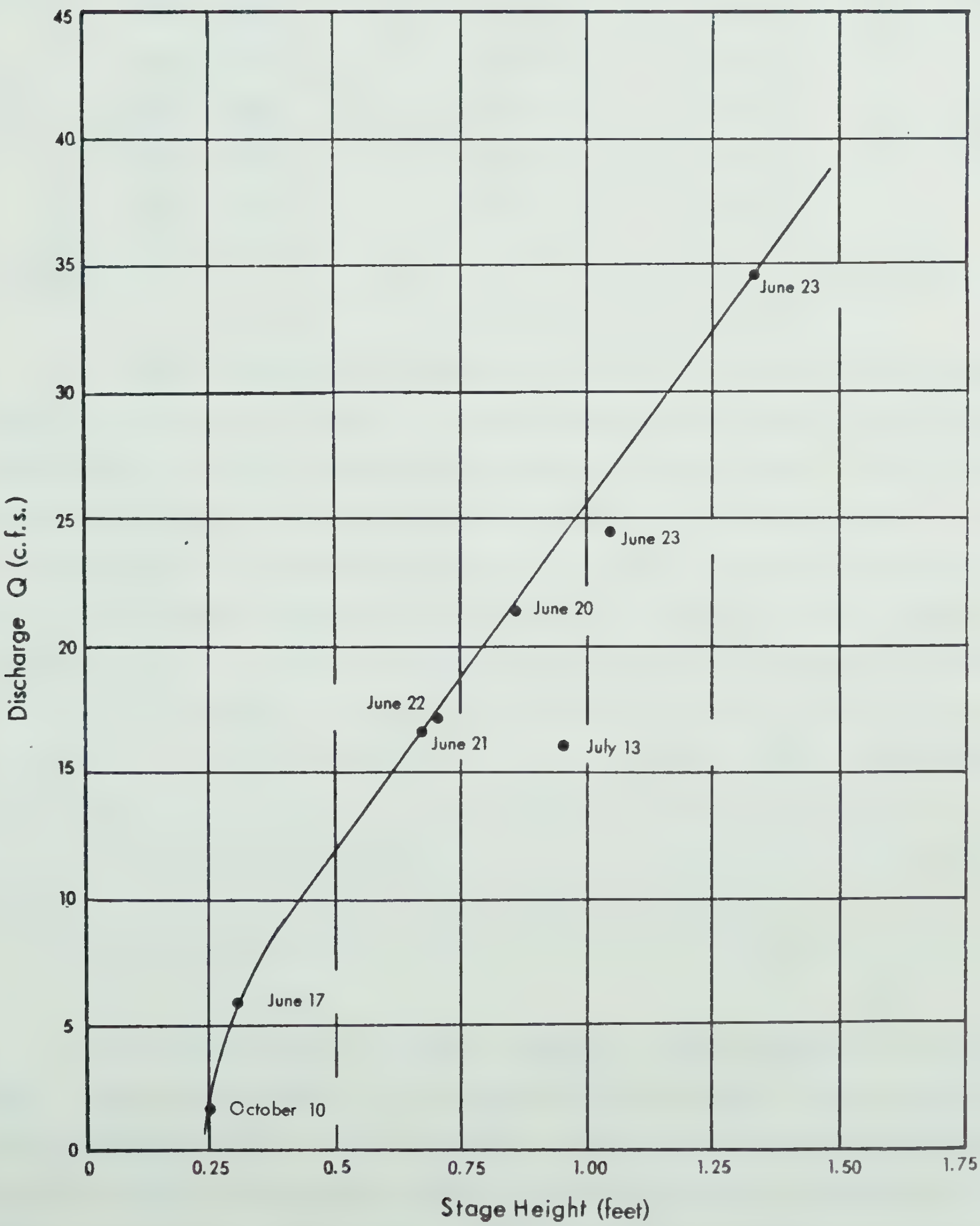


TABLE IV.1.

STAGE HEIGHT - DISCHARGE MEASUREMENTS

TWO O'CLOCK CREEK 1971

	Date	Time	Stage (ft.)	Discharge (c.f.s.)
1	17th June	11.00	0.30	6.0
2	20th June	20.30	0.85	21.3
3	21st June	10.45	0.66	16.5
4	22nd June	14.00	0.70	17.1
5	23rd June	10.15	1.04	24.6
6	23rd June	14.00	1.35	34.5
7	13th July	20.30	0.90	15.9
8	10th October	10.00	0.25	1.7

This regularity in discharge variations meant that although a continuous daily water level recorder was not available, high and low stages could be watched for at the times outlined above. As a result of these observations, an approximate mean daily discharge graph for Two O'Clock Creek is presented in Figure 4.2. This gives an indication of the change in water discharge throughout the study period. Figure 4.2. is qualified by the fact that although numerous stage height readings were made during high flow periods, at low flows only one reading per day or one every two days was recorded. As a result of the inevitable inaccuracies in this method of discharge estimation, no quantitative measure of total sediment yield for the study period has been made. Instead, estimations of bed-load transport are made for only the high flow periods when discharge could be reasonably determined (see Section 5.4.).

Rating curves in Bridge Creek are constructed for two different sites. Prior to the 5th of June when the weir burst, discharges were taken below the weir. After the 5th of June the stream bypassed the original gauging site and a second site was selected near the bed-load sampler, upstream of the weir. These two rating curves are shown in

TABLE IV.2.

STAGE HEIGHT - DISCHARGE RELATIONSHIPS
TWO O'CLOCK CREEK 1971

Date	Time	Stage Height (feet)	Discharge (c.f.s.)	Date	Time	Stage Height (feet)	Discharge (c.f.s.)
June 18	12.00	0.35	8.0	July 6	18.00	0.32	7.0
19	8.00	0.40	9.0	7	18.30	0.32	7.0
19	19.30	0.65	16.0	8	17.30	0.34	7.5
20	10.00	0.55	13.0	9	17.00	0.38	8.5
20	20.30	0.85	21.5	10	16.45	0.45	10.0
21	10.45	0.66	16.5	12	18.00	0.50	12.0
21	12.00	0.66	16.5	13	9.45	0.28	5.0
21	19.45	1.00	25.0	13	18.00	0.68	17.0
22	11.00	0.58	14.5	13	21.30	0.72	18.0
22	14.00	0.68	17.0	14	9.00	0.34	7.5
22	17.30	1.00	25.0	14	13.30	0.58	14.5
23	10.15	1.00	25.0	14	18.30	1.05	26.0
23	14.00	1.30	34.5	15	10.30	0.38	8.5
23	17.30	1.50	38.0	15	14.00	0.70	17.5
23	20.00	1.17	30.5	15	18.00	0.90	23.0
24	10.00	0.68	17.0	16	10.30	0.45	10.0
24	18.30	0.68	17.0	16	19.00	0.80	20.0
25	10.45	0.55	13.0	17	18.00	0.80	20.0
26	12.00	0.45	10.0	18	18.30	0.75	19.0
26	20.00	0.40	9.0	19	17.30	0.82	21.0
27	11.30	0.32	7.0	20	17.30	0.82	21.0
27	13.00	0.32	7.0	21	20.00	0.82	21.0
28	15.00	0.32	7.0	22	20.00	0.75	19.0
29	18.00	0.32	7.0	23	20.00	0.42	9.5
30	19.00	0.32	7.0	24	19.00	0.42	9.5
July 2	20.30	0.30	6.5	25	19.30	0.40	9.0
3	17.00	0.30	6.5	26	20.00	0.45	10.0
4	18.00	0.30	6.5	27	18.30	0.40	9.0
5	17.00	0.30	6.5	28	18.45	0.55	13.0

FIGURE 4.2

PRECIPITATION,MAXIMUM AIR TEMPERATURE AND APPROXIMATE DAILY WATER DISCHARGE TWO O'CLOCK CREEK 1971

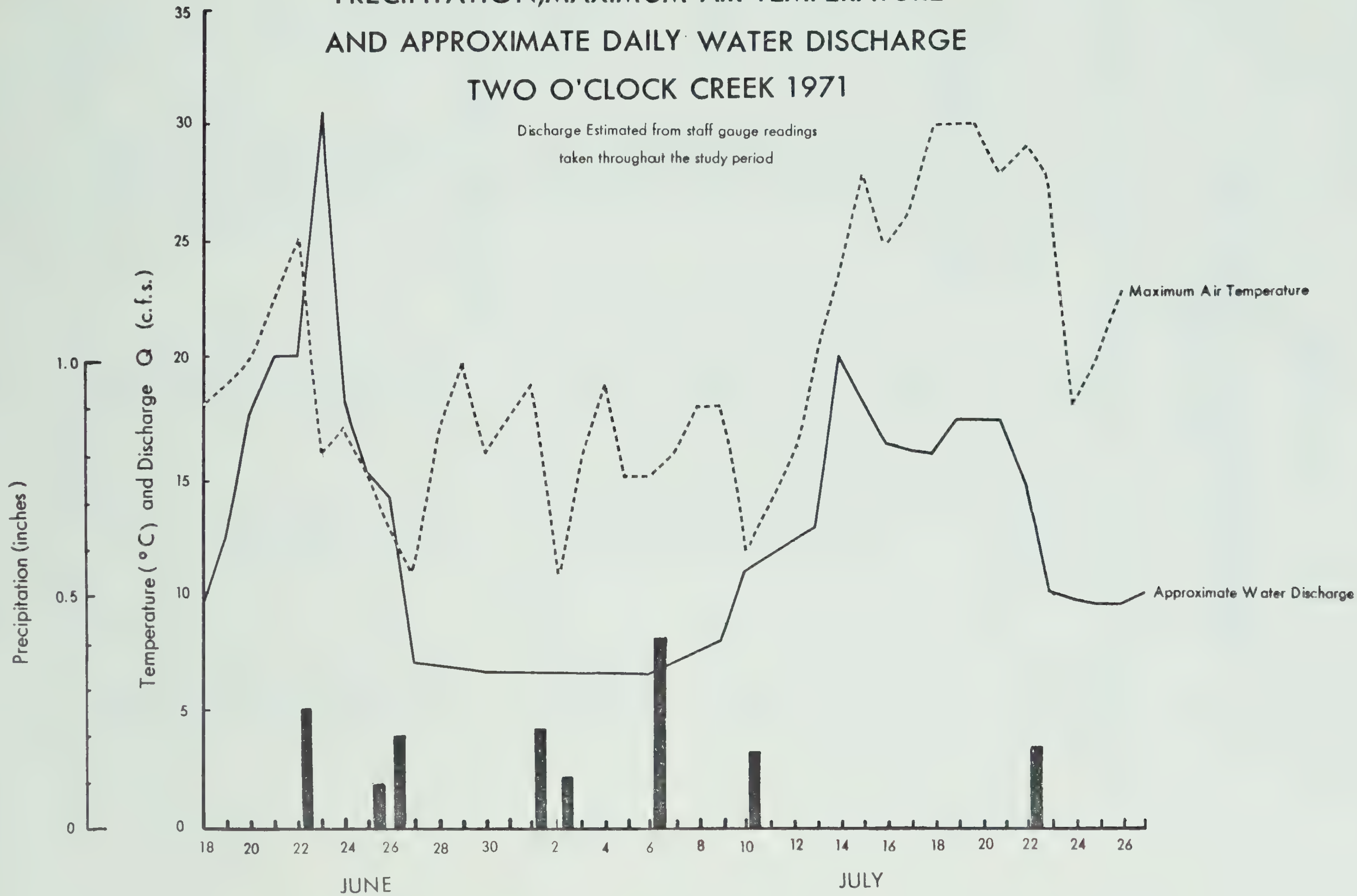


TABLE IV.3.

STAGE HEIGHT - DISCHARGE MEASUREMENTS

BRIDGE CREEK 1971

	Date	Time	Stage Height (feet)	Discharge (c.f.s.)
14th May to 4th June				
1	May 14	10.00	-	5.9
2	May 21	17.00	1.05	6.3
3	May 22	16.45	1.15	7.9
4	May 23	11.00	1.05	6.6
5	May 25	14.30	1.25	9.6
6	May 26	17.00	1.75	19.7
7	May 28	11.00	1.35	9.8
8	May 31	17.00	1.56	14.9
9	June 3	14.00	1.70	17.3
10	June 4	13.50	1.68	15.7
6th June to 10th October				
1	June 6	16.30	2.80	34.0
2	June 7	12.15	2.70	23.6
3	June 8	15.00	2.60	28.2
4	June 10	16.30	2.38	16.2
5	June 12	18.00	2.43	18.9
6	June 16	21.30	2.25	11.4
7	June 23	17.00	2.70	35.0
8	July 14	21.00	2.45	23.5
9	October 10	15.00	2.00	2.9

Figures 4.3a and 4.3b with individual discharge and velocity measurements given in Table IV.3.

Using the measurements made by the continuous recording hydrograph, a mean daily discharge graph is constructed for Bridge Creek in Figure 4.4. On this figure are plotted daily maximum and daily minimum temperatures as well as recorded rainfall.

4.3. Discharge-Climate Relationships

4.3.1. Bridge Creek

A steady increase in air temperature throughout May (Figure 4.4.) produced a progressive increase in stream discharge. This occurred in a series of increasing diurnal fluctuations, an example of such a fluctuation being shown in Plate 8. The diurnal peaks were observed to occur between 1800 and 2100 hours when snow melt produced by daily temperature increases was the controlling factor. Similarly, the lowest daily discharges occurred between 1000 and 1200 hours. In the presence of significant rainfall, these diurnal fluctuations became disrupted and peaks were controlled by rainfall and resulting snow melt.

The peak seasonal flow occurred after three days of rain culminating in a night of heavy thunderstorms on the 4th and 5th of June. The 1.7 inches of rain recorded at the weir site on Bridge Creek presumably activated the winter snow pack resulting in a peak flow that damaged the weir. Because the stream bypassed the water level recorder at this time, an accurate estimation of the peak flow is not possible. Even the highest point on the continuous trace immediately prior to the shifting of the stream is unsuitable to use because it would require an unreasonable extrapolation of the discharge rating curve. As a result no quantitative measurements are made based on the peak flow.

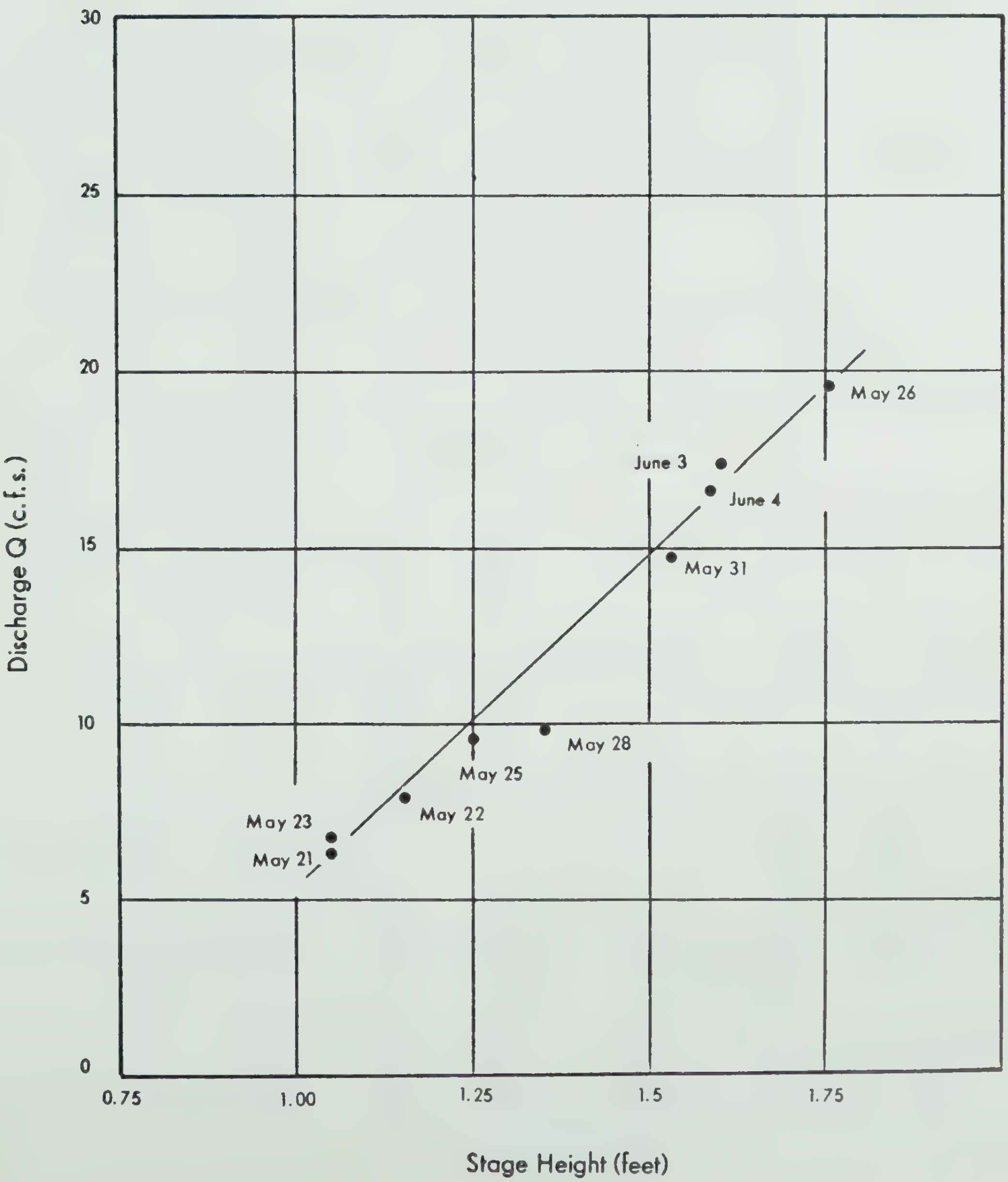
From the 5th of June to the 17th of June water level declined as did the daily temperatures. Observations in the catchment revealed snow fields still present on north facing slopes (Plates 1 and 2). The effect of rising temperatures causing diurnal snow melt can be seen again on the 23rd of June and on the 13th, 14th and 15th of July, producing small discharge peaks (Figure 4.4.).

From the seasonal peak flow on the 5th of June until the end of

DISCHARGE RATING CURVE BRIDGE CREEK

14th MAY to 4th JUNE 1971

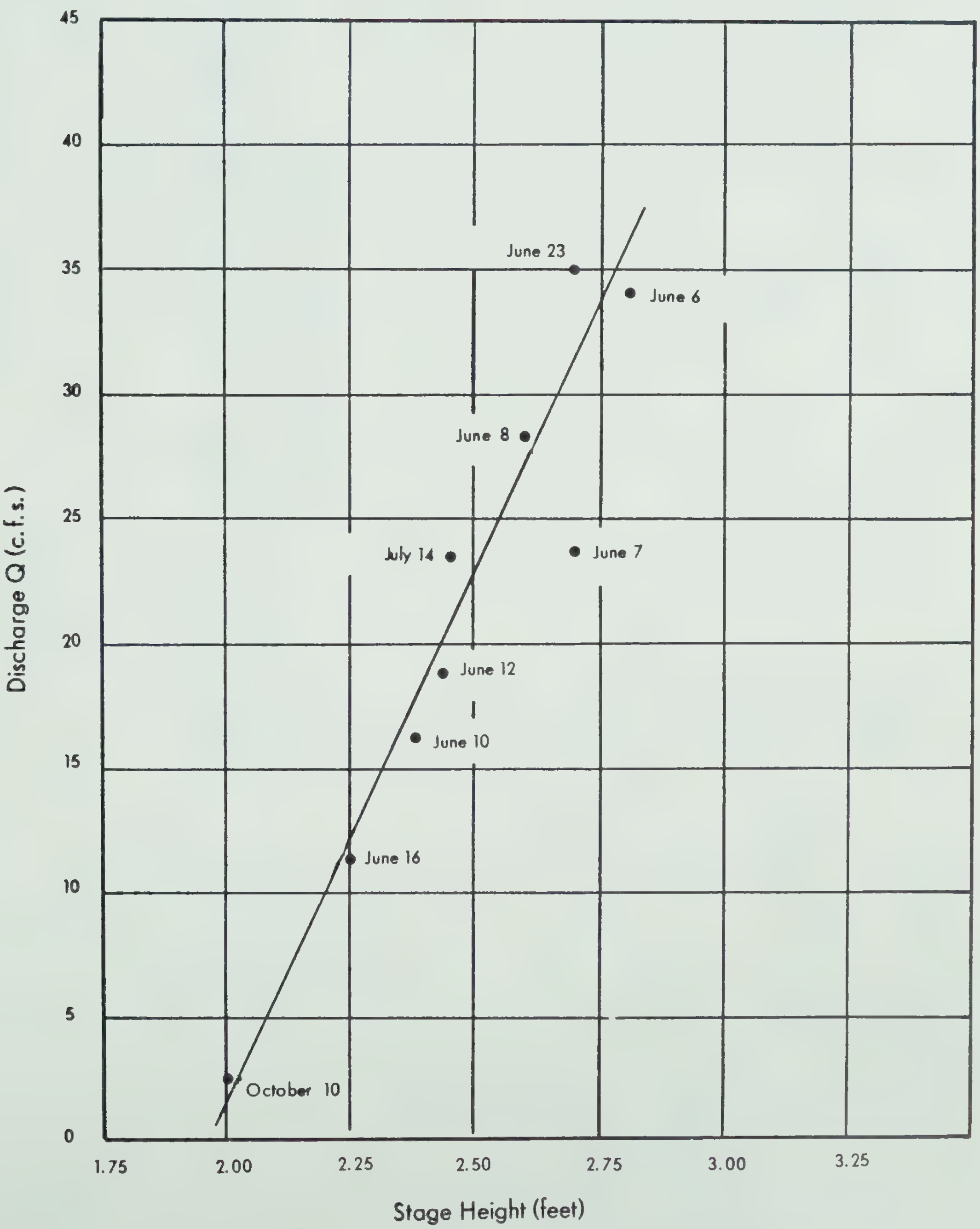
FIGURE 4.3a



DISCHARGE RATING CURVE BRIDGE CREEK

6th JUNE to 10th OCTOBER 1971

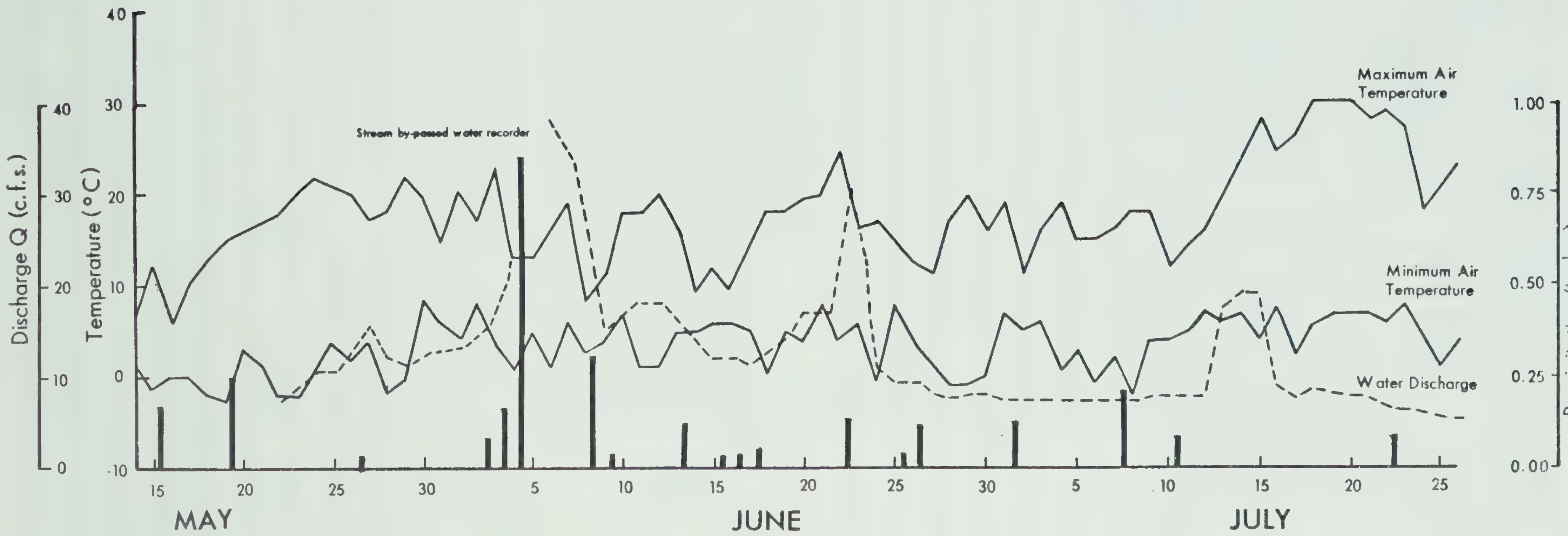
FIGURE 4.3b



DISCHARGE, PRECIPITATION AND AIR TEMPERATURE

BRIDGE CREEK, 1971

FIGURE 4.4



the field season, rainfall did not cause any peak flows noticeable on the water level trace. From the 16th of July until the end of the study period rising temperatures did not produce any noticeable runoff peaks, as all but a few patches of snow had dissipated.

4.3.2. Two O'Clock Creek

It is not possible to relate water discharge to climate in Two O'Clock Creek basin except in a general sense, because of the lack of a continuous water level recording. Using the stage height readings as described in the approximate mean daily discharge graph (Figure 4.2.) certain relationships are evident however.

The major peak flow measured during the study period from the 18th of June to the 25th of July occurred on the 23rd of June. This was induced by rising temperatures (Figure 4.2.) but was not the first high flow of the season. Two O'Clock Creek was observed to be running very high at the same time as the peak occurred on Bridge Creek on the 5th of June. No record of discharge was being taken on Two O'Clock Creek at that time.

Throughout the study period on Two O'Clock Creek, the high flows were observed to be controlled by snow melt induced by temperature increases and there was no evidence of flow peaks due to the light rain that fell during this period (Figure 4.2.).

4.4. Channel Geometry

Five cross sections were measured at varying discharges on each stream. A discussion of the techniques used is contained in Section 3.4. The results of these surveys are shown in Tables IV.4. and IV.5.

At high flows the water contained in each cross section spilled over the immediate flood plain. As a result a veneer of water three to four inches deep travelled down slope over this area. Because this water contributed very little to the total water discharge or bed-load discharge, the cross-sectional width of the stream was determined by drawing the channel cross sections and outlining the parabolic shape of the channel (or channels). The wings of water on either side of each cross section were thus excluded and this helped prevent an over-estimation of width and an under-estimation of stream depth for use in the empirical bed-load

TABLE IV.4.

CHANNEL GEOMETRY

BRIDGE CREEK 1971

Date	Discharge (c.f.s.)	Cross Section		Ave. Depth (feet)		Width (feet)		Velocity (f.p.s.)
June 9	18.0	A		0.71		8.5		
		B		0.50		11.5		
		C		0.95		10.5		
		D		0.76		7.5		
		E		0.71		7.5		
			$\bar{d}$	0.73	$\bar{w}$	9.1	$\bar{v}$	2.71
June 22	25.0	A		0.62		11.0		
		B		0.68		10.0		
		C		0.71		9.5		
		D		0.81		12.0		
		E		0.79		11.0		
			$\bar{d}$	0.72	$\bar{w}$	10.7	$\bar{v}$	3.24
July 14	23.0	A		0.60		12.0		
		B		0.66		10.8		
		C		0.74		8.8		
		D		0.89		9.3		
		E		0.88		10.6		
			$\bar{d}$	0.75	$\bar{w}$	10.3	$\bar{v}$	3.01
October 10	2.9	A		0.43		6.3		
		B		0.35		6.9		
		C		0.54		6.6		
		D		0.41		6.9		
		E		0.33		5.9		
			$\bar{d}$	0.41	$\bar{w}$	6.5	$\bar{v}$	1.08

TABLE IV.5.

CHANNEL GEOMETRY

TWO O'CLOCK CREEK 1971

Date	Discharge (c.f.s.)	Cross Section	Ave. Depth (feet)	Width (feet)	Velocity (f.p.s.)
June 23	34.5	A	0.72	14.3	
		B	1.11	9.8	
		C	0.73	16.0	
		D	0.61	17.9	
		E	0.89	10.0	
			$\bar{d}$ 0.81	$\bar{w}$ 13.6	$\bar{v}$ 3.13
June 25	13.0	A	0.47	9.1	
		B	0.35	9.8	
		C	0.39	11.3	
		D	0.44	11.2	
		E	0.43	11.0	
			$\bar{d}$ 0.42	$\bar{w}$ 10.5	$\bar{v}$ 2.95
July 14	21.5	A	0.55	15.0	
		B	0.61	9.2	
		C	0.52	14.3	
		D	0.56	10.9	
		E	0.79	10.0	
			$\bar{d}$ 0.61	$\bar{w}$ 11.9	$\bar{v}$ 2.96
October 10	1.7	A	0.26	5.0	
		B	0.24	6.6	
		C	0.23	12.2	
		D	0.30	2.2	
		E	0.36	8.2	
			$\bar{d}$ 0.28	$\bar{w}$ 6.8	$\bar{v}$ 0.89

formulae.

The results of these channel geometry measurements for Bridge Creek are shown in Figure 4.5. One anomaly with these results when observing the actual points plotted is that despite the adjustments described above, the depth measurements made at 26 c.f.s. dropped slightly compared with those made at lower stages. An average line is drawn through the points in Figure 4.5. in an attempt to reconstruct the conditions of flow in the section of the channel where the bed-load is being transported.

The results of the channel geometry measurements for Two O'Clock Creek are shown in Figure 4.6. Depth increases very little up to approximately 13 c.f.s. and then rises dramatically. Width shows a relatively constant increase. The velocity which has been calculated from width, depth and discharge indicates a rapid increase up to approximately 13 c.f.s. and then a more gentle increase.

Insufficient field observations were made to explain these differences between Bridge and Two O'Clock Creeks. Unlike Bridge Creek, however, the breaks in slope on the depth and the velocity lines in Figure 4.6. are thought to be sharp enough to necessitate the drawing of best fit lines through the actual points, rather than attempting an average line.

4.5. Slope Observations

For Bridge Creek, slope was measured with a theodolite and staff along the right bank of the stream at the waters edge. The flow at the time was approximately 10 c.f.s. and the levels were read every 100 feet over a distance of 900 feet above the reservoir. The average of nine readings which ranged from 0.0494* to 0.1006 was 0.0671. This value is used in the empirical bed-load formulae equations. Because of the step-like profile of the channel bed, composed of steep and gentle facets of slope, it is possible that mean slope may be too great a value to use in these bed-load equations. Water and sediment travelling throughout the reach must be able to pass across the units of least slope. It is,

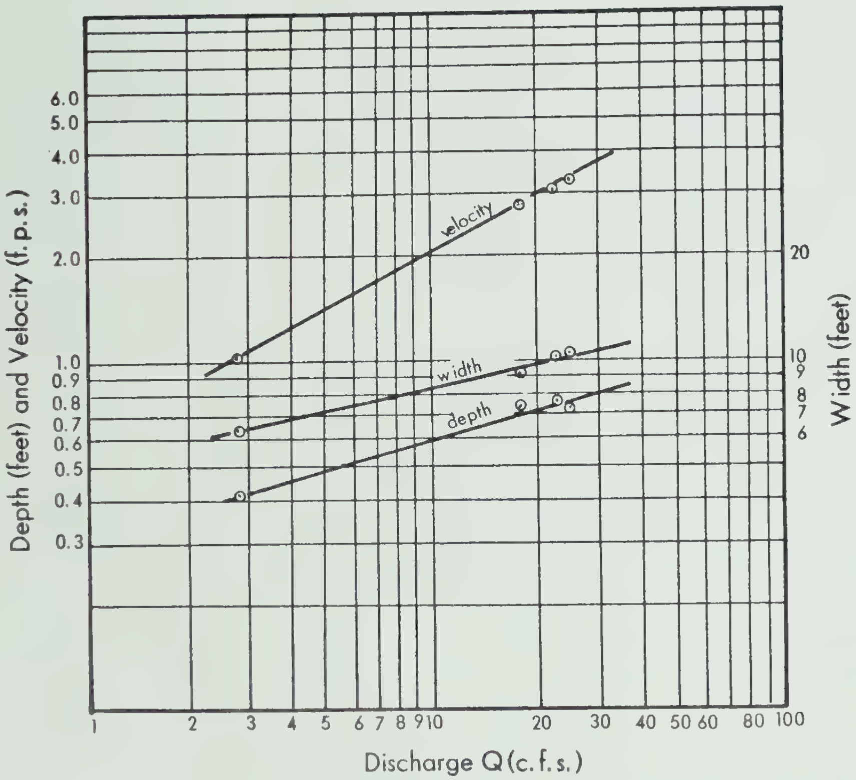
* Slopes are expressed as a ratio

FIGURE 4.5

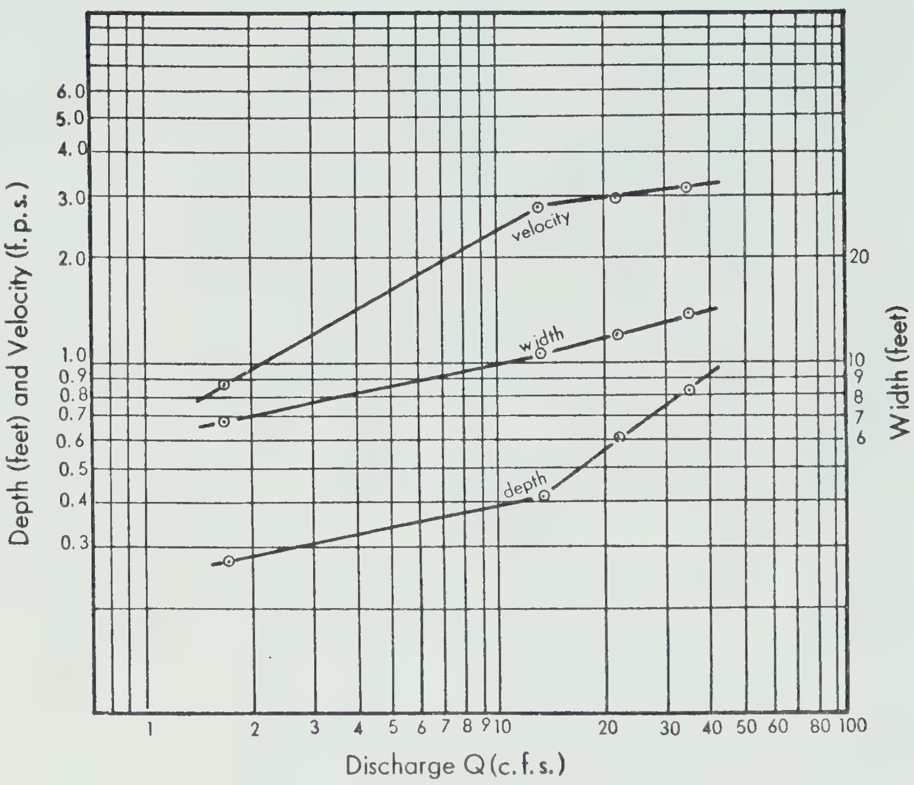
FIGURE 4.6

CHANNEL GEOMETRY

BRIDGE CREEK



TWO O'CLOCK CREEK



however, difficult to imagine how a more suitable figure than the mean slope could be arrived at when all the complexities of variable slope involved are taken into account.

McPherson (1971b) measured the longitudinal profile of Two O'Clock Creek from its source to its junction with the North Saskatchewan. Using data from these measurements (pers. comm. McPherson, 1971), the mean stream slope from the discharge site on Two O'Clock Creek to above the weir was determined. Because of the close proximity of the bedrock to the bed of the stream, it was not considered possible that the slope over such a distance could have changed significantly in the two years since these measurements were made. They were surveyed over a distance of 850 feet of channel length and slopes ranged from 0.200 to 0.083. The average slope of 0.114 was the most representative throughout the reach and is used in the computations of the bed-load equations.

4.6. Water Temperature

In both streams, water temperatures were recorded with a hand held thermometer at intervals throughout the season (Table IV.6.).

Only those temperatures taken when the discharge was in excess of that required for bed-load transport (see Sections 5.4. and 5.5.) have been averaged to obtain the mean water temperature for use in bed-load equations. In both streams this mean temperature was 43°F. The extremes of water temperature were observed in Bridge Creek with values of 34°F to 50°F. There was no obvious pattern visable throughout the season but this is possibly due to the lack of a continuous recording. McPherson (1971a) reports a very close agreement between air and water temperature patterns throughout the summer of 1969 in Two O'Clock Creek.

TABLE IV.6.

WATER TEMPERATURES

BRIDGE CREEK 1971

Date	Time	Temp. (F°)	Discharge (Q) (c.f.s.)	Date	Time	Temp. (F°)	Discharge (Q) (c.f.s.)
May 13	17.00	38	-	June 3	9.00	39	14.0*
14	10.00	34	6.0	3	12.00	50	15.0*
14	15.00	42	6.0	4	12.00	44	17.5*
15	11.40	44	-	5	18.00	38	-
17	10.00	40	-	6	11.30	40	-
21	11.00	44	-	6	13.00	42	-
21	15.30	48	4.2	6	14.00	43	-
22	11.30	46	5.5	6	15.00	44	38.0*
22	16.45	48	7.9	6	17.15	42	34.0*
23	10.30	44	6.5	7	12.00	44	28.0*
24	13.30	50	8.3	7	13.30	44	28.0*
24	17.00	42	14.5*	8	14.00	39	25.0*
24	19.00	40	12.0*	8	16.30	38	26.0*
25	11.00	44	8.5	9	14.00	39	19.0*
25	15.15	48	11.0*	9	15.00	39	19.0*
25	17.00	42	12.0	9	17.00	38	18.0*
26	10.00	44	9.0	10	16.30	45	16.0
26	16.00	45	17.5*	11	12.00	43	18.0*
26	17.30	42	19.8*	12	12.00	48	16.0
26	20.00	43	17.5*	12	18.00	44	19.0*
27	12.45	44	12.0*	14	12.00	42	12.0
27	17.00	40	15.0*	14	13.30	44	12.0
28	11.00	42	9.7	20	16.00	49	16.0
28	14.00	49	12.0*	23	19.00	40	32.0*
29	12.39	50	10.5*	27	19.30	42	8.0
30	14.00	46	11.0*	July 15	18.30	50	23.0*
30	19.00	41	15.0*	19	20.30	48	19.0
30	20.30	39	15.0*	22	20.30	48	10.0
31	17.00	44	14.8*				

* Discharge greater than that required for bed-load transport (see Sections 5.4. and 5.5.).

... cont'd.

TABLE IV.6. (cont'd.)

WATER TEMPERATURES

TWO O'CLOCK CREEK 1971

Date	Time	Temp. (F°)	Discharge (Q) (c.f.s.)	Date	Time	Temp. (F°)	Discharge (Q) (c.f.s.)
June 20	20.30	40	21.0*	June 25	10.45	48	14.0*
21	10.45	42	14.0	26	12.00	43	10.0
21	20.30	40	24.0*	27	13.00	42	7.0
22	11.00	47	14.0	July 10	16.45	44	10.0
22	17.30	45	25.0*	13	18.00	45	17.0*
23	10.15	42	23.0*	14	18.30	45	27.0*
23	12.00	40	26.0*	15	18.00	49	23.0*
23	19.15	44	32.0*	19	19.30	48	19.0*
24	10.00	44	17.0*	22	20.00	48	18.0*
24	18.30	44	17.0*	23	17.00	46	13.0

* Discharge greater than that required for bed-load transport (see Sections 5.4. and 5.5.).

CHAPTER V

OBSERVATIONS AND ANALYSIS OF SEDIMENT TRANSPORT

5.1. Introduction

In this chapter, observations of suspended load and bed-load transport in Bridge Creek and bed-load transport in Two O'Clock Creek are recorded and analysed. Total sediment yield results are not possible for either stream because complete seasonal records were not taken for Two O'Clock Creek and records were interrupted at the peak flow in Bridge Creek. The sediment transport pattern is analysed throughout the study period on Bridge Creek and these results are plotted graphically and examined statistically. Tentative relationships between water discharge and bed-load discharge are also established for both streams.

5.2. Bed-load Grain Size Analysis

From the material accumulating behind each weir, three bulk samples were selected for grain size analysis of bed-load material in each stream. The grain size analyses for these individual samples are given in Appendix B and shown graphically in Figures 5.1a and 5.1b. In Bridge Creek, one bulk sample was taken on the stream bed from a point bar deposit that had recently been covered by flood water. This sample was taken from a point 50 feet above the pool behind Bridge Creek weir.

Two mean percentage grain size curves are constructed using the three weir samples in Two O'Clock Creek and the three weir samples and one stream bed sample in Bridge Creek (Figure 5.2.).

5.3. Suspended Load Sampling in Bridge Creek

Suspended sediment samples were taken in Two O'Clock Creek during the summers of 1969 and 1970 (McPherson, 1971; pers. comm. McPherson, unpublished data, 1972). For this reason and because of the longer study period on Bridge Creek, suspended sediment sampling was restricted to this stream during the summer of 1971.

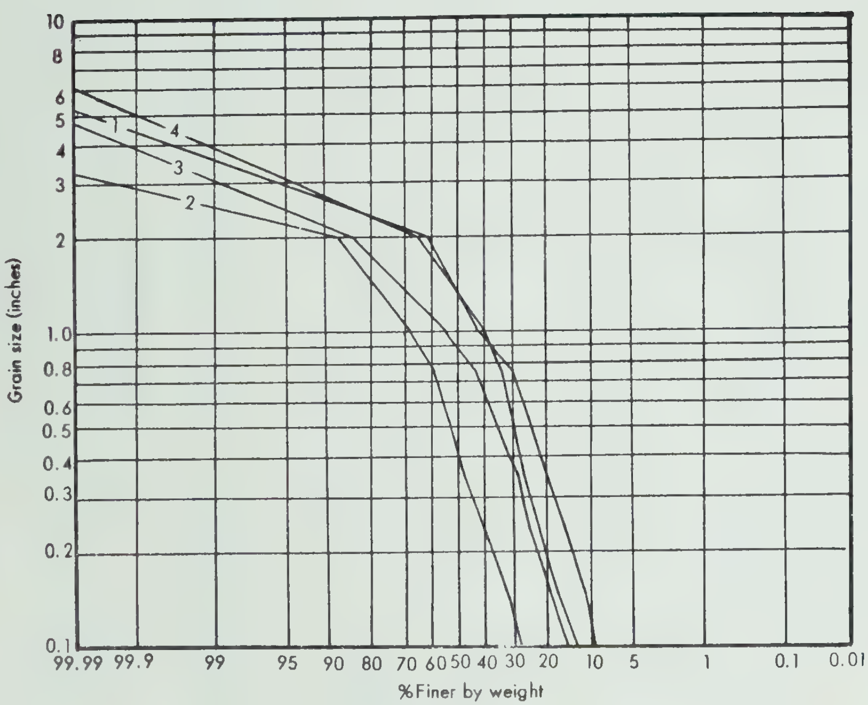
The results of suspended sediment sampling on Bridge Creek are

FIGURE 5.1a

GRAIN SIZE DISTRIBUTIONS

FIGURE 5.1b

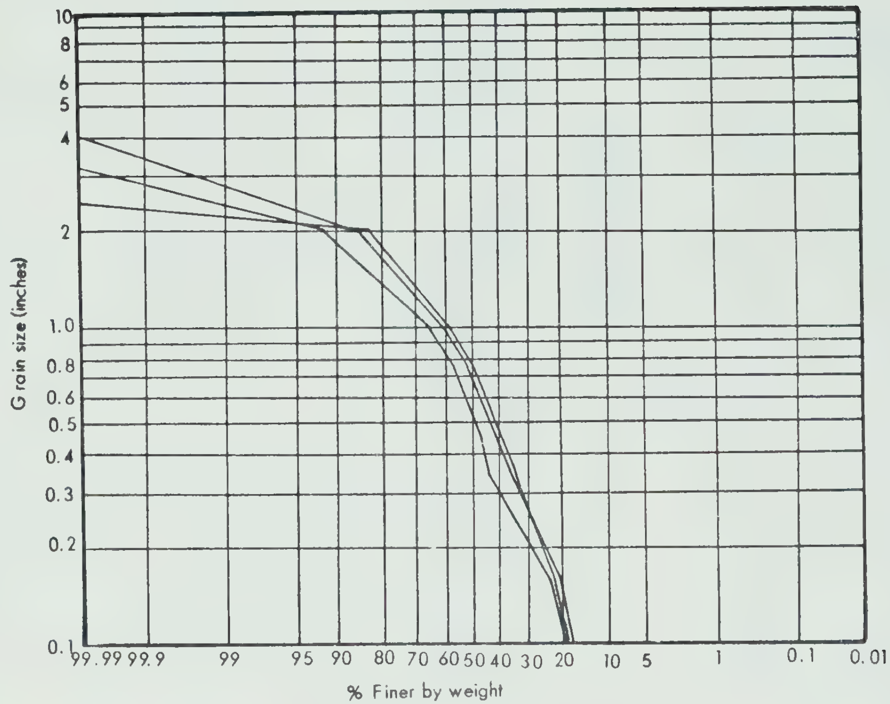
BRIDGE CREEK



Samples 1, 2 and 3 from the weir

Sample 4 from a point bar deposit

TWO O'CLOCK CREEK



3 Samples from the weir

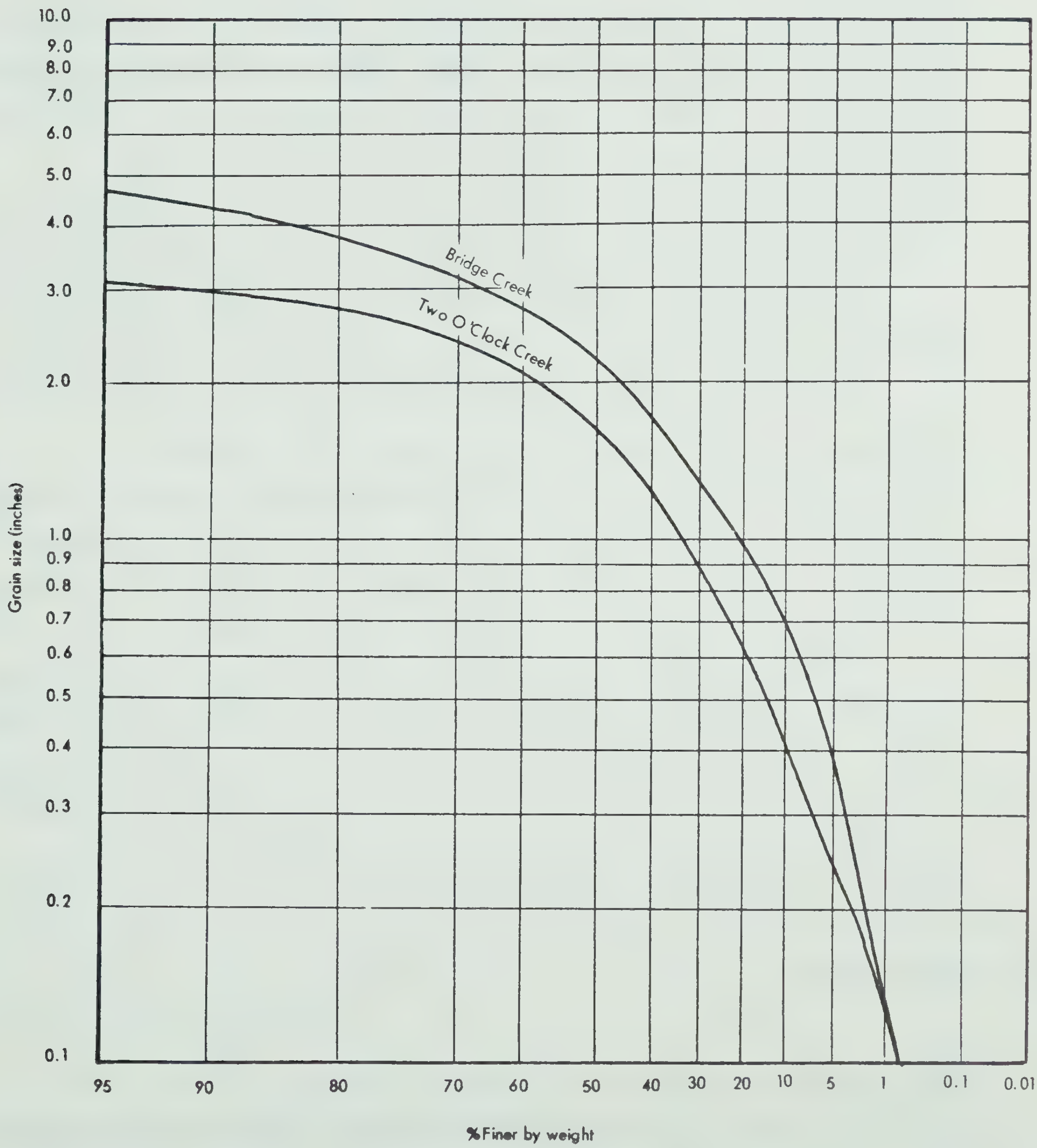
MEAN PERCENTAGE GRAIN SIZE CURVES

Bridge Creek :3 Weir Samples and 1 Stream Bed Sample

Two O'Clock :3 Weir Samples

Volumetric Pit Samples

FIGURE 5.2



given in Table V.1. and plotted graphically in Figure 5.3. A linear regression line based on all the points in this figure is described by the equation

$$C_s = 8.91 \times 10^{-3} \times Q^{1.03}$$

where C_s = suspended sediment concentration.

The correlation coefficient for this relationship is 0.362 and is significant at the 1 per cent level. However the total variance explained by the relationship is only 13.1 per cent.

From observations made in the field based on the degree of discolouration of the water in Bridge Creek, it appears that in this catchment, the suspended load concentration/water discharge ratio declines as the season progresses. Low water discharges at the beginning of the runoff season were more discoloured due to suspended sediment than similar or higher discharges later in the season.

To support these visual field observations, the sample points plotted in Figure 5.3. are subdivided into three groups: those samples collected early in the runoff season, those collected in the middle period and those collected towards the end of the season. An examination of Figure 5.3. supports these visual observations. Samples collected between May 21st and May 26th plot well to the left in Figure 5.3. Samples taken between May 27th and June 5th fall into the centre and those sampled after June 5th plot to the right in the graph. June 5th is selected as a significant date for the division of the data because this was the occasion of the peak seasonal discharge for 1971. May 27th, however, is an arbitrary choice based on what appears to be a natural break in the points plotted. Regression lines are drawn for each of the three groups of points on Figure 5.3. and the results of these regressions are presented in Table V.2.

To test the hypothesis that the sediment concentration/water discharge ratio changes sequentially as the runoff season progresses on Bridge Creek, a step-up multiple regression analysis is used to determine the degree of influence that factors other than water discharge have on the suspended sediment concentration.

SUSPENDED SEDIMENT RATING CURVES

BRIDGE CREEK 1971

FIGURE 5.3

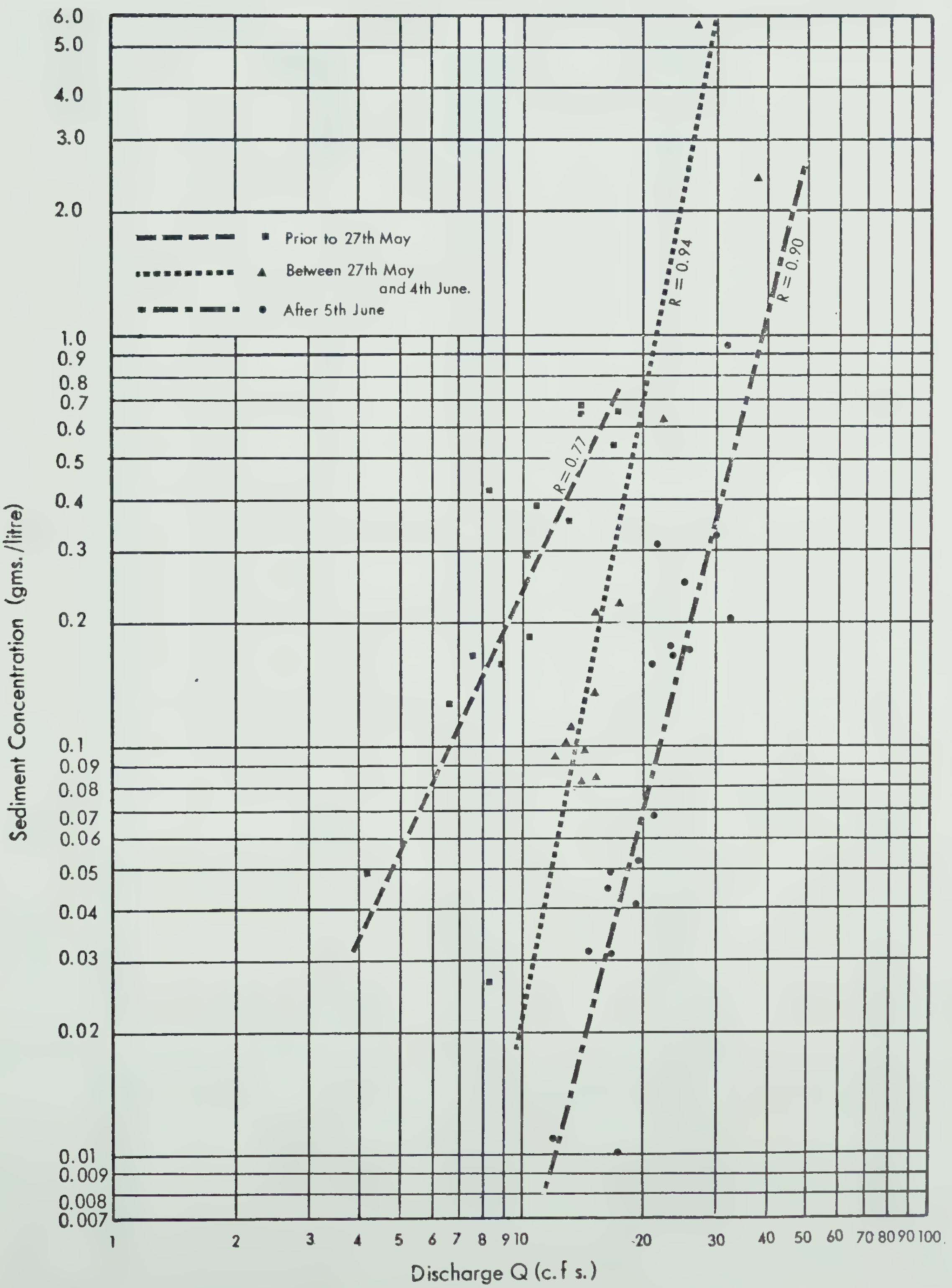


TABLE V.1.

SUSPENDED SAMPLE ANALYSES

BRIDGE CREEK 1971

Sample No.	Date	Time	Sed. Conc. g/1	Discharge Q c.f.s.
1	May 21	15.30	0.0502	4.2
2	22	15.30	0.1686	7.8
3	24	14.00	0.4118	8.3
4	24	17.00	0.6589	14.0
5	24	19.00	0.6992	14.0
6	24	20.00	0.3507	13.0
7	25	11.00	0.0278	8.2
8	25	14.00	0.1595	9.0
9	25	17.00	0.2975	11.5
10	25	20.00	0.1848	11.5
11	26	14.00	0.3909	11.0
12	26	20.00	0.6773	17.5
13	27	14.00	0.1016	13.0
14	27	20.00	0.2133	15.5
15	28	14.00	0.0949	12.0
16	28	20.00	0.1105	13.5
17	29	17.00	0.0835	14.0
18	30	17.00	0.1377	15.0
19	30	20.00	0.0980	14.0
20	31	20.00	0.2260	16.0
21	June 3	20.00	0.6244	22.0
22	4	14.00	0.0855	15.0
23	4	17.00	5.5371	26.0
24	6	15.00	2.3922	38.0
25	7	14.00	0.3382	30.0
26	7	17.00	0.2040	32.0
27	7	20.00	0.1412	30.0
28	8	17.00	0.2528	25.0
29	8	20.00	0.3128	22.0
30	9	20.00	0.0495	16.5
31	10	14.00	0.0329	14.5
32	12	20.00	0.0102	17.5
33	13	14.00	0.0310	16.5
34	17	20.00	0.0116	12.0
35	19	18.00	0.0466	16.5
36	20	21.30	0.0680	21.0
37	21	10.15	0.1756	25.0
38	23	19.00	0.9462	32.0
39	24	18.00	0.0530	19.0
40	July 13	18.30	0.1601	21.0
41	14	21.30	0.1688	23.4
42	15	18.30	0.1702	23.4
43	19	20.30	0.0410	19.0

TABLE V.2.

REGRESSION ANALYSIS OF SEDIMENT CONCENTRATION VS DISCHARGE FOR THREE TIME PERIODS ON BRIDGE CREEK SUMMER 1971

Time Interval	Correlation Coefficient R	Result of T Test
21st May-26th May	0.766	Significant at 0.2 per cent level
27th May-4th June	0.940	Significant at 0.1 per cent level
6th June-19th July	0.903	Significant at 0.1 per cent level

The dependent variable, sediment concentration, is tested against the independent variables of water discharge (Q c.f.s.) at the time of sampling, the number of days after the start of the runoff season that the sample was taken on (date) and the rate of change of water level at the time of sampling (rate). An analysis of variance (F test) is used to ascertain whether the increment to the explained variance made by the additional independent variable is significantly different from zero. This regression technique is useful for establishing the relative importance of the independent variables on sediment concentration. A significance level of 0.05 is selected for the F test. Each of the independent variables is successively added to the equation in the order of the magnitude of their contribution to the explained variance. The results of the analysis are shown in Table V.3. These results show that suspended load concentration is controlled most significantly by discharge and that in addition there is a significant change in the suspended sediment concentration, depending on whether the suspended samples are taken early in the runoff season or later in the season, even when discharge is held constant. The hypothesis that the suspended concentration/water discharge ratio declines as the runoff season proceeds in Bridge Creek, appears valid.

TABLE V.3.

STEP-UP REGRESSION OF SUSPENDED SEDIMENT CONCENTRATION
VS DISCHARGE (Q), DATE AND RATE
BRIDGE CREEK 1971

Independent Variable	Degrees of Freedom	Total explained Variance %	Variance Added %	Result of F test $\alpha = 5\%$
Discharge (Q)	1 and 41	15.4	15.4	Significant at 1% level
Discharge (Q) Date	2 and 40	23.5	8.1	Significant at 5% level
Discharge (Q) Date Rate	3 and 39	24.3	0.8	Not significant

These results are not in conflict with those found by other researchers. Colby (1963) states that the discharge of fine particles is controlled by the availability of supply of such particles and the supply is usually less than the stream can support.

Milhous and Klingeman (1971) found that the sampling of suspended sediment samples in a small mountain stream in the Oregon Coastal Range "produced a considerable scatter of points as is typical of suspended loads which are dependent upon the availability of the particles for transport". They noted during their analysis that the first high flows transported more suspended sediment than later flows of similar or greater magnitude.

Hall (1967), in discussing the pattern of sediment movement on the Tyne River in England, found that the sediment concentration/water discharge ratio changed significantly between summer and winter (Figure 7, p. 128). This he explains is the result of higher rainfall intensities during higher runoff and surface erosion. During the winter, rainfall is largely frontal and less intense.

Brown (1972) also reports seasonal differences in the sediment

rating curves of streams in the Tumut Valley in south-eastern New South Wales, Australia. In a study of the effects of bush fires on suspended sediment yield he uses separate summer and winter rating curves as the suspended sediment concentration/water discharge ratio is considerably higher in the summer.

Judging from the recent literature it is not unexpected to find seasonal differences in the suspended sediment concentration/water discharge ratio. Possible influencing factors controlling changes in this ratio are discussed along with factors influencing changes in the bed-load concentration/water discharge ratio in Section 5.6. at the end of this chapter.

5.4. Weir Survey Results and Analysis

5.4.1. Two O'Clock Creek Weir Survey Results

These results are shown in Table V.4. and details of water discharge over the survey period are shown in Figures 5.4a and 5.4b.

The initial survey of the pool behind the Two O'Clock Creek weir was made on the 18th June at 11 a.m. The discharge was below 10 c.f.s. and no bed-load transport was observed. A series of increasing diurnal discharge fluctuations carried 25,053 lbs. of sediment into the pool by the 21st of June. The largest accumulations occurred on the 22nd and 23rd of June with 54,521 lbs. and 99,680 lbs. respectively. On the evening of the 23rd of June, the front portion of sediment behind the weir was excavated and a new level surveyed. On the 25th, 26th and 27th of June a much larger portion was excavated in preparation for further runoff from snow fields still observable in the catchment.

From the 24th of June to the 16th of July, only the front 107 points (instead of the full 234 points) were used in the surveys. The remainder of the reservoir was a flat deltaic surface with relatively little change in elevation and was not surveyed because the major volume change occurred in the excavated section along the front of the developing delta.

The pool was re-surveyed after the excavation period, on the 27th of June. Very little bed-load accumulated up until the 13th of July, reflecting the low water discharges (Figure 4.2.). On the 13th and 14th

TABLE V.4.

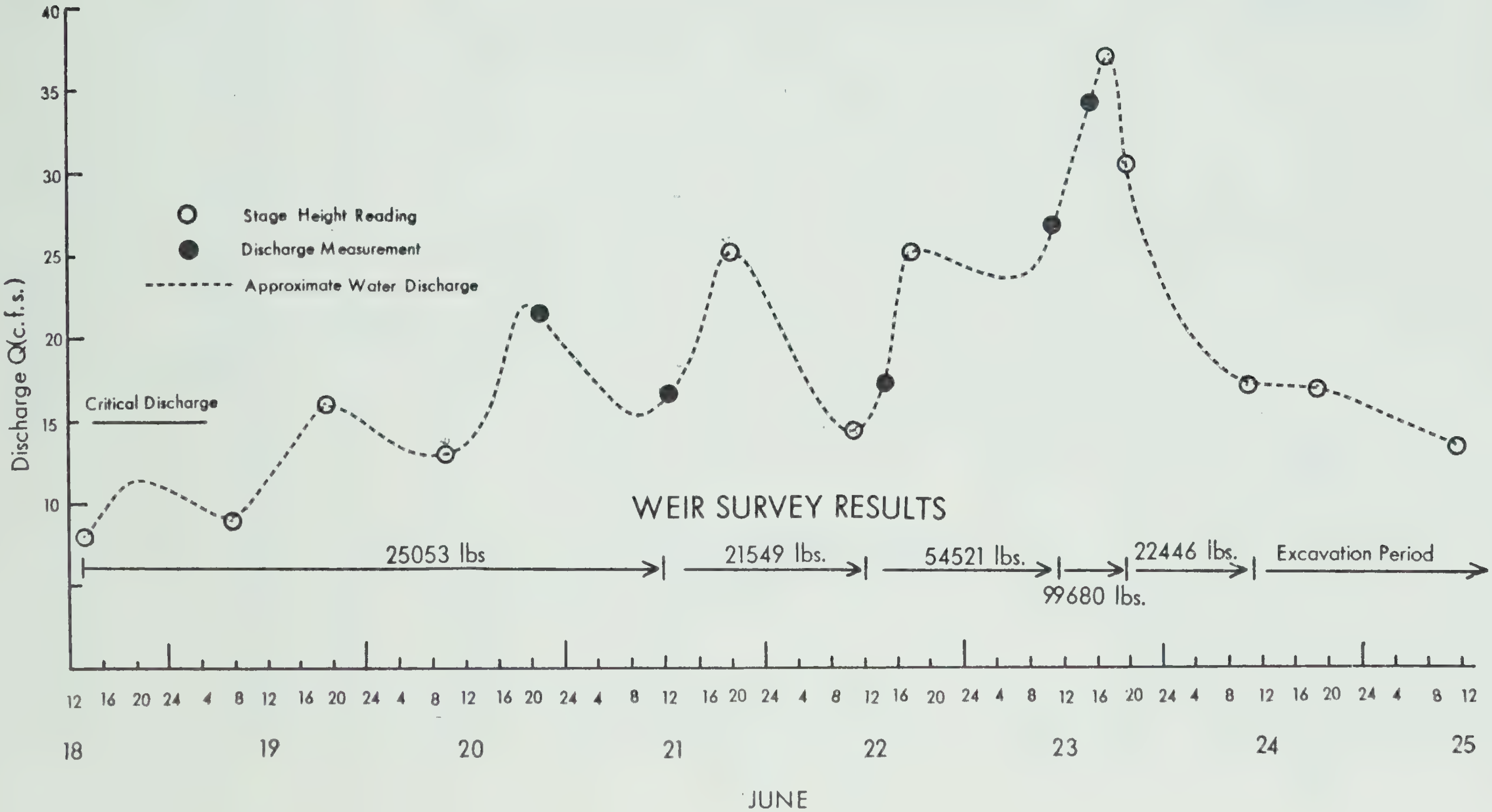
WEIR SURVEYS - TWO O'CLOCK CREEK 1971

Date of Survey	Time	No. of Points	Survey Level (ft.)	Area (sq. ft.)	Sediment Volume (cu. ft.)	Sediment Weight* (lbs.)	Remarks
June 18	11.00	214	7.016	856	-	-	Initial survey
21	12.00	214	7.700	856	184.9	25,053	
21	12.00	234	7.620	936	-	-	More points added
22	12.00	234	7.450	936	159.1	21,549	
23	10.30	234	7.024	936	398.7	54,521	
23	18.00	234	6.237	936	736.6	99,680	
23	20.00	234	6.326	936	-	-	Sediment excavated
24	10.00	234	6.149	936	165.7	22,446	
24-27			Sediment excavation - No record was kept				
27	12.00	107	6.925	428	-	-	Initial survey
July 8	12.00	107	6.867	428	24.8	3,360	
13	12.00	107	6.870	428	0.0	0	
15	11.00	107	6.370	428	212.5	28,851	
15	12.00	107	6.786	428	-	-	Sediment excavated
16	10.30	107	6.584	428	86.4	11,693	
16	12.00	107	6.860	428	-	-	Sediment excavated
22	11.00	107	6.057	428	347.9	47,139	

* One cubic foot of oven dried sediment 135.5 lbs.

FIGURE 5.4.a

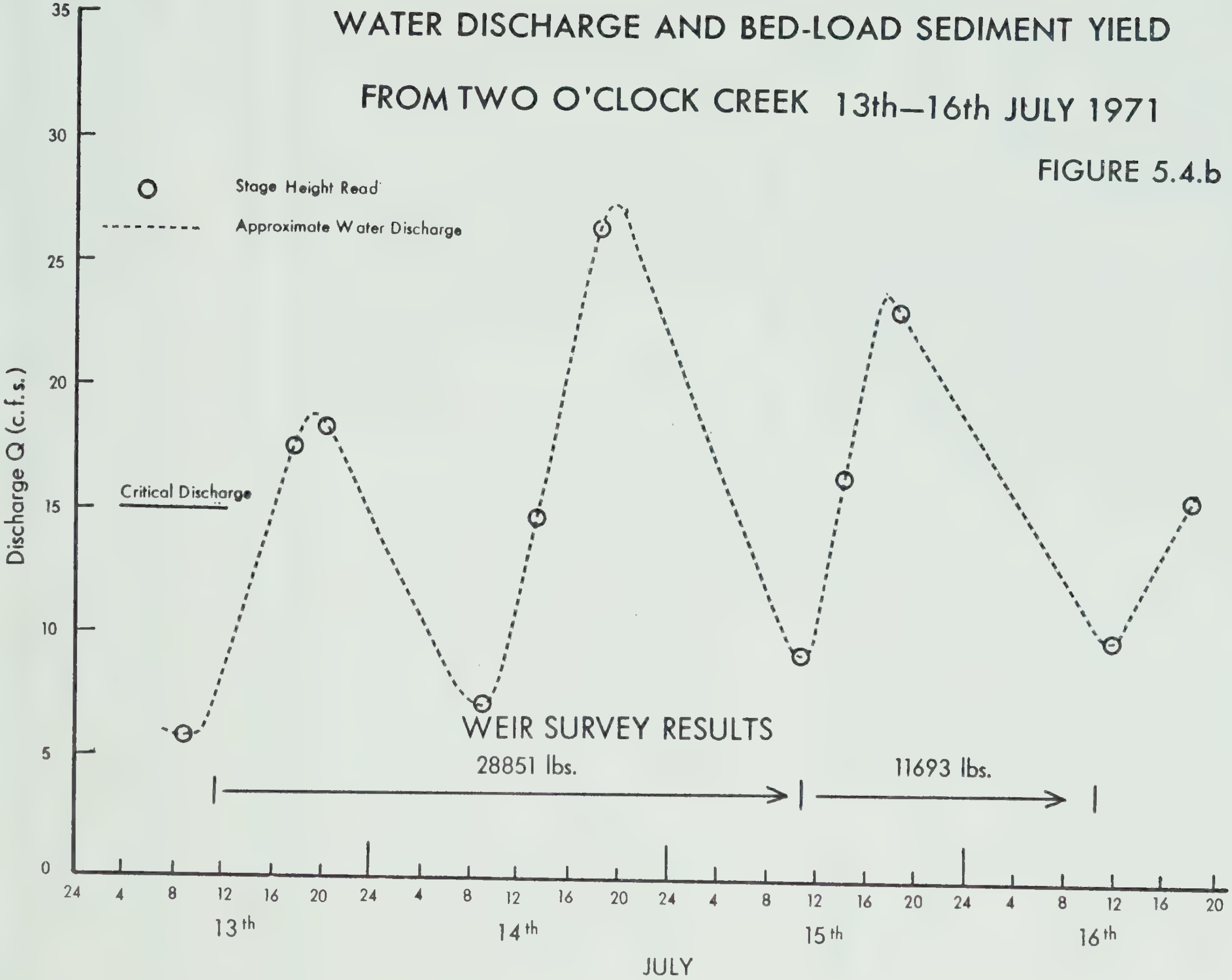
WATER DISCHARGE AND BED-LOAD SEDIMENT YIELD FROM TWO O'CLOCK CREEK 18th—24th JUNE 1971



WATER DISCHARGE AND BED-LOAD SEDIMENT YIELD

FROM TWO O'CLOCK CREEK 13th–16th JULY 1971

FIGURE 5.4.b



of July 28,851 lbs. accumulated. The final survey of the season was conducted on the 22nd of July when 47,139 lbs. of bed-load accumulated.

To determine the bed-load transport rating curve for Two O'Clock Creek, certain weir survey results were discarded from the analysis. The first accumulation period (18th to 21st of June) is not used because of the uncertainty that on the 18th of June the discharge did not reach the critical value required for bed-load transport (Figure 5.4a). The survey result measured on the 8th of July is also not used because discharge was not observed accurately enough over this low flow period to be certain that an unrecorded fluctuation did not occur. For the same reason, the result measured on the 22nd of July is not used (Table V.4.). The remaining six survey results are analysed to determine the bed-load transport rate for Two O'Clock Creek over the study period.

5.4.2. Two O'Clock Creek Weir Survey Analysis

For the purpose of relating bed-load discharge to water discharge, the critical discharge for bed-load transport was determined in the field. From visual observations and by wading the stream during channel geometry and discharge measurements, it was found that incipient movement of bed material started at approximately 15 c.f.s. in Two O'Clock Creek. For the establishment of a bed-load - water discharge relationship, detailed hydrographs based on stage height and discharge readings for high flow periods are constructed (Figures 5.4a and 5.4b). The following procedures are used to determine the bed-load transport rate:

1) The time that the stream discharge exceeds 15 c.f.s. during the period of accumulation is recorded from Figures 5.4a and 5.4b (Column 2, Table V.5.).

2) The mean discharge between 15 c.f.s. (or the lowest discharge for the period of accumulation - whichever is the greater) and the peak discharge for the period of accumulation is determined (Column 3, Table V.5.). (The mean discharge has been applied and found to be a satisfactorily accurate parameter despite the exponential relationship between water discharge and bed-load.)

3) The total bed-load accumulation in lbs. for the period between weir surveys is recorded (Column 4, Table V.5.).

4) The total bed-load accumulation in lbs. is divided by the number of minutes that the discharge exceeded 15 c.f.s. between weir surveys to determine the transport rate in lbs. per minute (Column 5, Table V.5.).

5) The transport rate in lbs. per minute is plotted against the mean water discharge (No. 2 above) in Figure 5.5. to obtain a bed-load rating curve.

TABLE V.5.

BED-LOAD CHARGE AS COMPUTED FROM WEIR SURVEYS ON TWO O'CLOCK CREEK 1971

1 Date of bed-load movement	2 No. of hours discharge >15 c.f.s.	3 Mean discharge >15 c.f.s.	4 Total bed-load catch in lbs.	5 G_s lbs./min.
21st June	18.0	20.10	21,549	19.95
22nd June	21.0	25.30	54,521	43.27
23rd June	7.5	33.00	99,680	221.50
23rd June	16.0	22.20	22,446	26.50
13th-14th July	22.0	21.25	28,851	21.85
15th July	14.0	19.25	11,693	13.92

When plotted as a rating curve in Figure 5.5. these results indicate that there is a close relationship between bed-load discharge and water discharge. By fitting a regression line to the points in this figure, bed-load transport for Two O'Clock Creek for the study period can be expressed by the power relation:

$$G_s = 5.93 \times 10^{-6} \, Q^{4.95}$$

where the correlation coefficient = 0.96 at a significance level of 0.1%.

5.4.3. Bridge Creek Weir Survey Results

The initial survey was conducted in the Bridge Creek weir on May 9th. The results of this and other surveys are shown in Table V.6.

Only 7,148 lbs. of bed-load accumulated behind the weir between May 9th and May 22nd. From this date until the 3rd of June, increasing

BED-LOAD DISCHARGE FROM WEIR SURVEY MEASUREMENTS

TWO O'CLOCK CREEK 1971

FIGURE 5.5

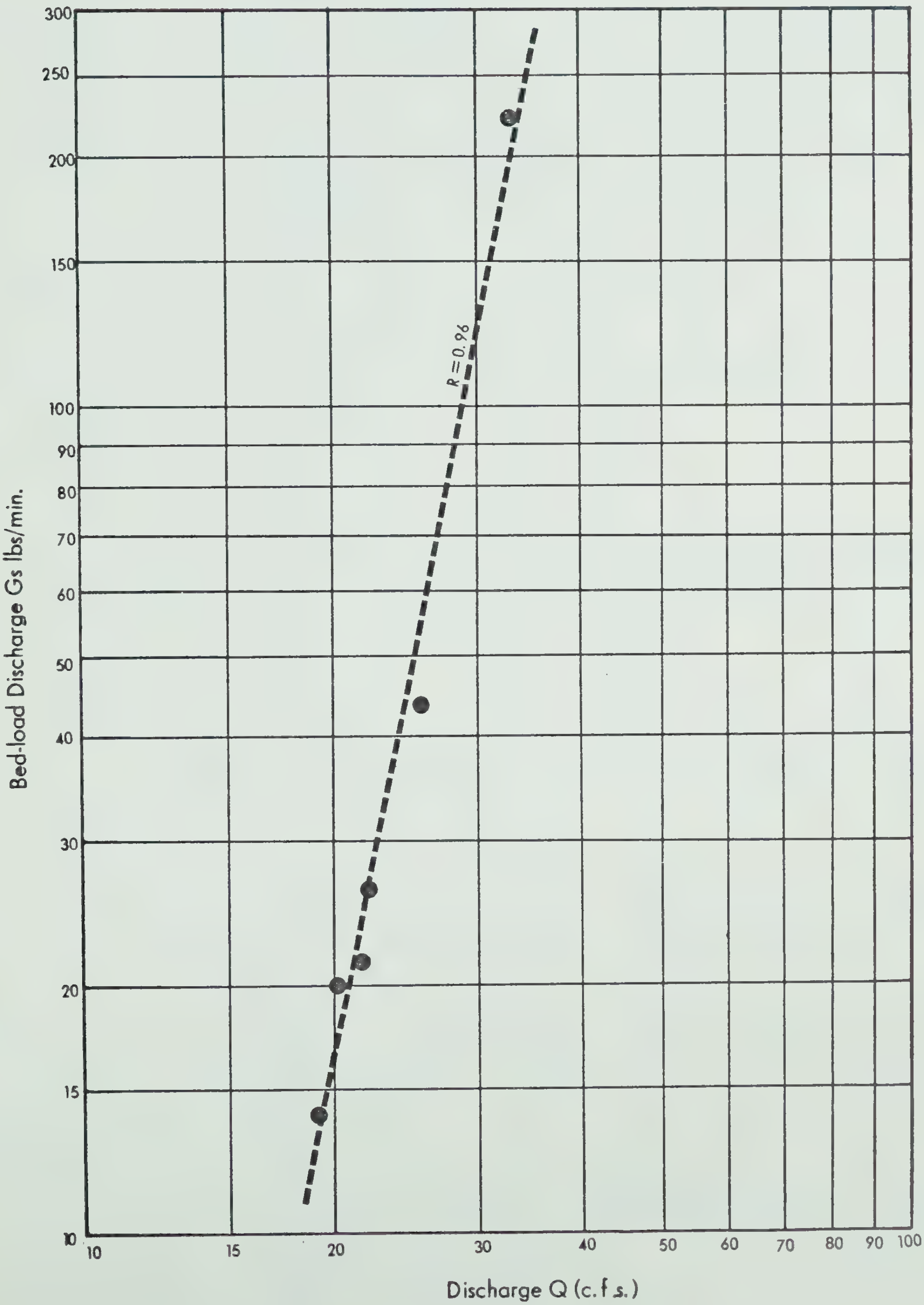


TABLE V.6.

WEIR SURVEYS - BRIDGE CREEK 1971

Date of Survey	Time	No. of Points	Survey Level (ft.)	Area (sq. ft.)	Sediment Volume (cu. ft.)	Sediment Weight* (lbs.)	Remarks
May 9	10.00	316	9.714	1,255.8	-	-	Initial survey
22	11.00	316	9.672	1,255.8	52.7	7,148	
June 3	11.30	134	8.417	1,255.8	1,576.8	213,651	
4	10.00	134	7.874	1,255.8	681.9	92,355	
4-15			Break in data due to weir collapse				
15	12.00	114	8.590	1,679.4	-	-	Initial survey
20	16.00	114	8.591	1,679.4	0.0	0	
21	16.00	114	8.586	1,679.4	0.0	0	
24	17.00	114	8.120	1,679.4	782.6	106,131	
24	17.00	216	8.251	1,679.4	-	-	Re-surveyed using 216 points
July 4	12.00	216	8.115	1,679.4	0.0	0	
15	14.00	216	8.115	1,679.4	0.0	0	

* One cubic foot of oven dried sediment 135.5 lbs.

diurnal fluctuations of discharge produced 213,651 lbs. of bed-load accumulation. Between June 3rd and June 4th, 92,355 lbs. of sediment accumulated in 22.5 hours.

The collapse of the weir at 1400 hours on the 5th of June prevented further measurements being made during the peak flow period. The weir was repaired and measurements started again on June 20th. After this, the only accumulation of any significance occurred on the 22nd June when the stream peaked to 33 c.f.s. and 106,131 lbs. of sediment accumulated.

Although the weir surveys were too infrequent on Bridge Creek to produce a meaningful rating curve, they are used as absolute values to check bed-load sampler results (see Section 5.5.2.).

Problems encountered with the Bridge Creek weir site resulted largely from the poor selection of a weir site.

5.5. Basket Sampling Results

The sampling results are given in detail in Appendix C.

The stream was sampled over three sections of channel width: the left bank (L.B.), the middle of the stream (M.S.) and the right bank (R.B.). The total bed width across the log sill at the sampling site was 7.5 feet and each of the three sections was 2.5 feet in width.

Because bed-load discharge fluctuates so significantly throughout any one sampling period, a mean value of bed-load discharge is calculated for each section of the channel width. These values are given in Table V.7. along with the mean water discharge for the sampling period.

5.5.1. Correction for Loss of Fines from the Basket Sampler

Because the bed-load sampler has a quarter inch wire mesh basket, it is assumed that there is a certain percentage of the total sampler catch that is washed through the mesh. This is particularly true at the beginning of the sampling period when the basket is empty. As the sampler fills with bed-load, this coarser material will act to trap particles finer than a quarter inch that would normally pass through. To determine what the average loss of fines is through the basket mesh, a selection of 14 samples caught in the sampler was sieved to determine

TABLE V.7.

BASKET SAMPLER - DISCHARGE RELATIONSHIPS

BRIDGE CREEK 1971

Date	Time Period	Position	Average Sampler Catch lbs/min. ft.	Bed-load Discharge per 1/3 of stream bed/min.	Total Bed-load Discharge lbs/min.	Stream Discharge c.f.s.
May 26	15.10-15.55	LB*	7.50	18.75	18.75	16.0
May 26	20.25-21.15	LB	10.00	25.00		
		MS	1.95	4.90	29.90	17.5
		RB	0.00	0.00		
May 27	17.45-18.30	LB	1.00	2.50		
		MS	2.80	7.00	9.50	16.0
		RB	0.00	0.00		
May 28	14.00-16.00	LB	1.80	4.50		
		MS	0.00	0.00	4.50	13.0
		RB	0.00	0.00		
May 28	19.20-19.43	LB	1.20	3.00		
		MS	0.10	0.25	3.25	14.0
		RB	0.00	0.00		
May 29	15.45-16.41	LB	1.10	2.75		
		MS	0.15	0.38	3.13	14.0
		RB	0.00	0.00		
May 30	14.30-15.30	LB	0.20	0.50		
		MS	0.60	1.50	2.00	12.0
		RB	0.00	0.00		
May 30	19.00-19.40	LB	0.62	1.55		
		MS	0.50	1.25	2.80	14.8
		RB	0.00	0.00		
May 30	19.45-20.22	LB	1.95	4.88		
		MS	0.10	0.25	5.13	15.2
		RB	0.00	0.00		

... cont'd.

TABLE V.7. (cont'd.)

BASKET SAMPLER - DISCHARGE RELATIONSHIPS

BRIDGE CREEK 1971

Date	Time	Position	Average Sampler Catch lbs/min. ft.	Bed-load Discharge per 1/3 of stream bed/min.	Total Bed-load Discharge lbs/min.	Stream Discharge c.f.s.
May 31	17.16-18.37	LB	1.41	3.53		
		MS	1.05	2.62	6.15	15.0
		RB	0.00	0.00		
June 6	14.00-15.10	LB	38.00	95.00		
		MS	56.00	140.00	235.00	38.0
		RB	0.00	0.00		
June 6	16.15-16.51	LB	21.00	52.50		
		MS	22.00	55.00	107.50	34.0
		RB	0.00	0.00		
June 7	14.20-16.00	LB	4.50	11.25		
		MS	13.00	32.50	48.75	28.0
		RB	2.00	5.00		
June 8	15.38-16.25	LB	10.70	35.75		
		MS	3.50	8.75	44.50	26.5
		RB	0.00	0.00		
June 9	15.00-15.30	LB	0.30	0.75		
		MS	0.50	1.25	2.00	18.5
		RB	0.00	0.00		
June 10	15.00-16.00	LB	0.20	0.50		
		MS	0.00	0.00	0.50	16.0
		RB	0.00	0.00		
June 12	18.00-18.30	LB	0.30	0.75		
		MS	0.15	0.38	1.13	18.5
		RB	0.00	0.00		
June 22	20.00-20.25	LB	0.00	0.00		
		MS	0.90	2.25	3.50	24.0
		RB	0.50	1.25		

* LB Left Bank
MS Mid Stream
RB Right Bank

what percentage of each sample was less than a quarter inch (Table V.8.).

TABLE V.8.

PERCENTAGE OF FINES LESS THAN 1/4 INCH
CAUGHT IN BASKET SAMPLER
BRIDGE CREEK 1971

Date	Discharge Q	Per cent	Date	Discharge Q c.f.s.	Per cent
25 May	13.0	13.20	29 May	14.0	28.50
26 May	17.5	37.60	30 May	12.5	11.28
26 May	16.0	3.22	30 May	15.0	10.80
27 May	16.0	15.04	30 May	15.0	21.60
27 May	16.0	12.55	31 May	15.0	24.70
28 May	14.0	36.55	6 June	38.0	12.80
28 May	14.0	28.40	7 June	28.0	15.98
		Mean percentage	19.50		

These results show that the amount of fines trapped is extremely variable. A mean value of 19.5 per cent of material < 1/4 inch is present in these 14 samples.

From the mean grain size curve for the material sampled in Bridge Creek weir and including the sample from the stream bed (Figure 5.2.), it appears that 25 per cent by weight is less than 1/4 inch. If it is assumed that these samples represent the bed-load of Bridge Creek, then the basket sampler with a mean catch of 19.5 per cent by weight being less than 1/4 inch in size, is losing 5.5 per cent as a result of fines passing through the mesh.

However the assumption that all the material less than 1/4 inch caught in the weir is bed-load is unlikely to be correct. A certain percentage of this material will be suspended load that has settled out of suspension behind the weir. As a result, the loss of fines through the basket sampler mesh is expected to be less than 5.5% and therefore probably well within the error of the sampling technique. It is concluded that the loss of fines through the sampler mesh in Bridge Creek is not significant.

5.5.2. Basket Sampler Rating Curves and Hydraulic Efficiencies

The results of the basket sampling of bed-load in Bridge Creek are given in Table V.7. and plotted as rating curves in Figure 5.6. A linear regression line based on all the points in Table V.7. is described by the equation

$$G_s = 2.02 \times 10^{-4} Q^{3.68}$$

where G_s = the bed-load discharge in lbs./min.
and Q = water discharge.

The correlation coefficient for this relationship is 0.786 and is significant at the 0.1 per cent level.

While plotting the points on Figure 5.6., it became apparent that there is a natural division of points between those plotted prior to the seasonal peak flow on the 5th of June and those plotted after the peak flow. For this reason two regression lines have been used to fit these data.

The equation for the linear regression line for the data prior to the peak flow is

$$G_s = 7.63 \times 10^{-8} Q^{6.78}$$

The correlation coefficient for this relationship is 0.85 and is significant at the 0.2 per cent level.

The equation for the linear regression line for the data after the peak flow is

$$G_s = 2.61 \times 10^{-10} Q^{7.68}$$

The correlation coefficient for this relationship is 0.96 and is significant at the 0.1 per cent level.

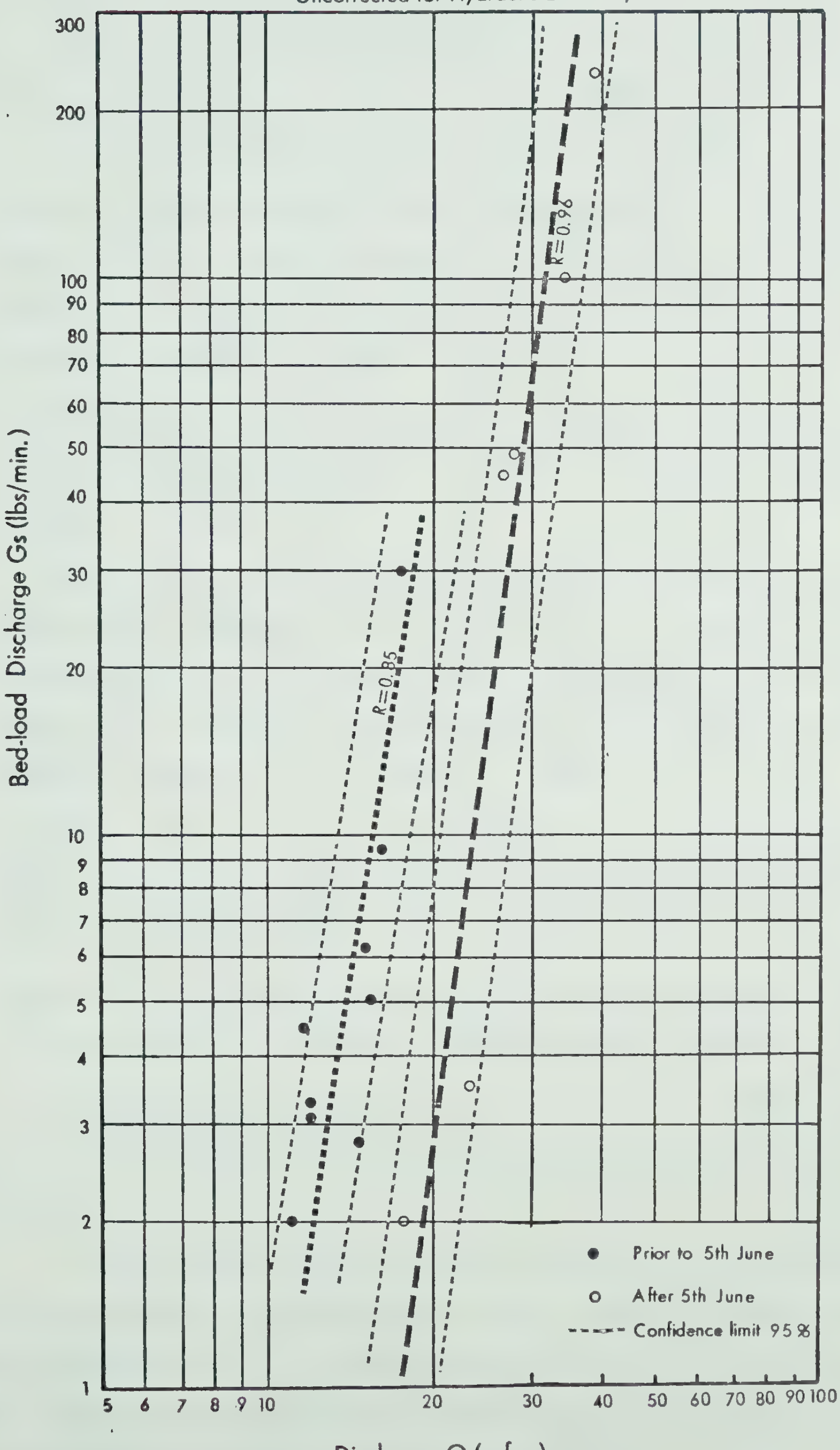
To determine the validity of assuming two separate populations of points in Figure 5.6., 95 per cent confidence limits have been included. These confidence limits show that the regression lines represent two different populations at a significance level of 5 per cent (pers. comm. E.S. Keeping, May 1972).

From these sampler observations in Figure 5.6., the critical discharges for bed-load transport in Bridge Creek are approximately 10

FIGURE 5.6

BED-LOAD DISCHARGE FROM BASKET SAMPLER MEASUREMENTS BRIDGE CREEK

Uncorrected for Hydraulic Efficiency



c.f.s. prior to the peak flow and 18 c.f.s. after the peak.

To determine the hydraulic efficiency of the basket sampler for high and low water discharges, the result of the total bed-load yield calculated between weir surveys from the basket sampler rating curves (Figure 5.6.), is expressed as a percentage of the amount of sediment actually caught in the Bridge Creek weir in the same period of time. Calculations of each day's bed-load yield from the sampler rating curves are outlined below and the results presented in Table V.9.

1) The mean water discharge value between the critical water discharge required for bed-load transport or the day's lowest discharge (whichever is the greater) and the highest peak discharge for that day, is determined (Column 2, Table V.9.).

2) The length of time each day that the stream discharge exceeds the critical discharge required for bed-load transport is determined (Column 3, Table V.9.).

3) The day's bed-load yield is calculated from Figure 5.6. by using the mean water discharge calculated in (1) to determine the bed-load transport rate in lbs./min. This is then multiplied by the number of minutes the discharge exceeds the critical discharge required for bed-load transport (2) (Column 4, Table V.9.).

4) Because of the infrequent surveyings of the Bridge Creek weir, the daily bed-load yields are summed for the period between weir surveys (Column 5, Table V.9.).

5) The sum of these daily bed-load yield calculations is then expressed as a percentage of the weir survey results (Column 7, Table V.9.).

The results in Table V.9. show that the basket sampler efficiency ranges from 25 per cent at low stream discharges to 75 per cent at high discharges.

Results from work recently completed in the hydraulics laboratory at the University of Alberta (pers. comm. Charles Gibbs, unpublished data, April 1972) show that in a laboratory flume and using a scaled down basket sampler model, the sampler's hydraulic efficiency ranged from 30 per cent at a bed-load discharge of 20 lbs./foot/minute to 50 per cent at 110

TABLE V.9.

COMPARISON BETWEEN BED-LOAD CAUGHT IN BRIDGE CREEK WEIR AND BASKET SAMPLER RESULTS 1971

1 Date	2 Mean Q when above 10 c.f.s.	3 No. of hrs. Q was above 10 c.f.s.	4 Basket Sampler Results (lbs.)	5 Accumulated Basket Sampler Results (lbs.)	6 Weir Survey (lbs.)	7 Basket Sampler as a % of Weir Catch
May 22	12.0	-	-		Initial survey	
23	12.0	0.0	0			
24	12.0	9.0	810			
25	12.0	9.5	855			
26	15.5	20.5	12,300			
27	13.0	20.0	3,300			
28	12.5	15.0	2,025			
29	12.5	17.0	1,530			
30	12.5	21.0	2,835			
31	13.0	21.0	3,465			
June 1	15.0	24.0	10,080			
2	15.5	24.0	14,400	51,600	213,651	24.15
3	20.0	22.0	69,400	69,400	92,355	75.10
	Mean Q when above 18 c.f.s.	No. of hrs. Q was above 18 c.f.s.				
June 19	20.0	3.0	225			
20	21.0	9.0	2,025			
21	21.0	9.0	2,025			
22	22.0	20.0	5,700			
23	26.5	12.0	16,560	26,535	106,131	25.00

lbs./foot/minute (the maximum experimental range). These results do not include losses due to fines as all grain sizes used were larger than the sampler mesh size.

Samide (1971) found that for the Elbow River in western Alberta, that the 1/4 inch mesh basket sampler efficiency increased from zero at near the critical discharge of 1200 c.f.s. to 35 per cent at 1400 c.f.s. and up to 45 per cent at 1600 c.f.s. Efficiency measurements beyond 1600 c.f.s. were not possible because the actual bed-load discharges were not known. It is possible on the basis of work by Gibbs that at higher discharges the efficiency would increase further still.

Hubbell (1964) attributes the basket sampler with an average efficiency of 45 per cent and it is this value that Hollingshead (1968) used in his study on the Elbow River.

Because only three efficiency estimations are available for Bridge Creek (Table V.10.), the basket sampler measurements are adjusted on the basis of the field measurements of Samide (1971) and the laboratory results of Gibbs (pers. comm., April 1972). The trend of both these researchers' results is similar to that found in Bridge Creek, where the sampler efficiency increases with increasing discharge.

Corrections are made on the basis of a straight line relationship between 30 per cent efficiency at bed-loads of 20 lbs./min. or less up to 50 per cent efficiency at bed-loads of 110 lbs./min. (pers. comm. Gibbs, April 1972). These corrections are included in Table V.11. and the corrected bed-load rating curves are plotted in Figure 5.7.

It is possible that the unusually high efficiency found for the basket sampler in Bridge Creek at high discharges (Table V.10.) is a function of unknown factors relating to the different hydraulic conditions found in a steep shallow mountain stream. As only one estimation was made at high discharges, further work would be required to establish this.

Using the corrected bed-load sampling values, bed-load transport for Bridge Creek can be expressed by the power relations

$$G_s = 2.55 \times 10^{-7} \, Q^{6.75}$$

where R = 0.85 and is significant at the 0.2% level prior to the seasonal peak discharge (Figure 5.7.), and

TABLE V.10.

CALCULATIONS OF BASKET SAMPLER EFFICIENCY FOR VARYING BED-LOAD DISCHARGES

BRIDGE CREEK 1971

Date	Range of Q above critical Q c.f.s.	Range G_s* lbs./min./ft.	Accumulated Basket Sampler Results lbs.	Weir Survey Result lbs.	Basket Sampler as % of the Weir Catch
May 22-June 2	10-20	0-60	51,600	213,651	24.15
June 3	15-23	70-140	69,400	92,355	75.10
June 19-23	18-32	0-90	26,535	106,131	25.00

* From Figure 5.6.

TABLE V.11.

CORRECTIONS OF THE BASKET SAMPLER RESULTS

BRIDGE CREEK 1971

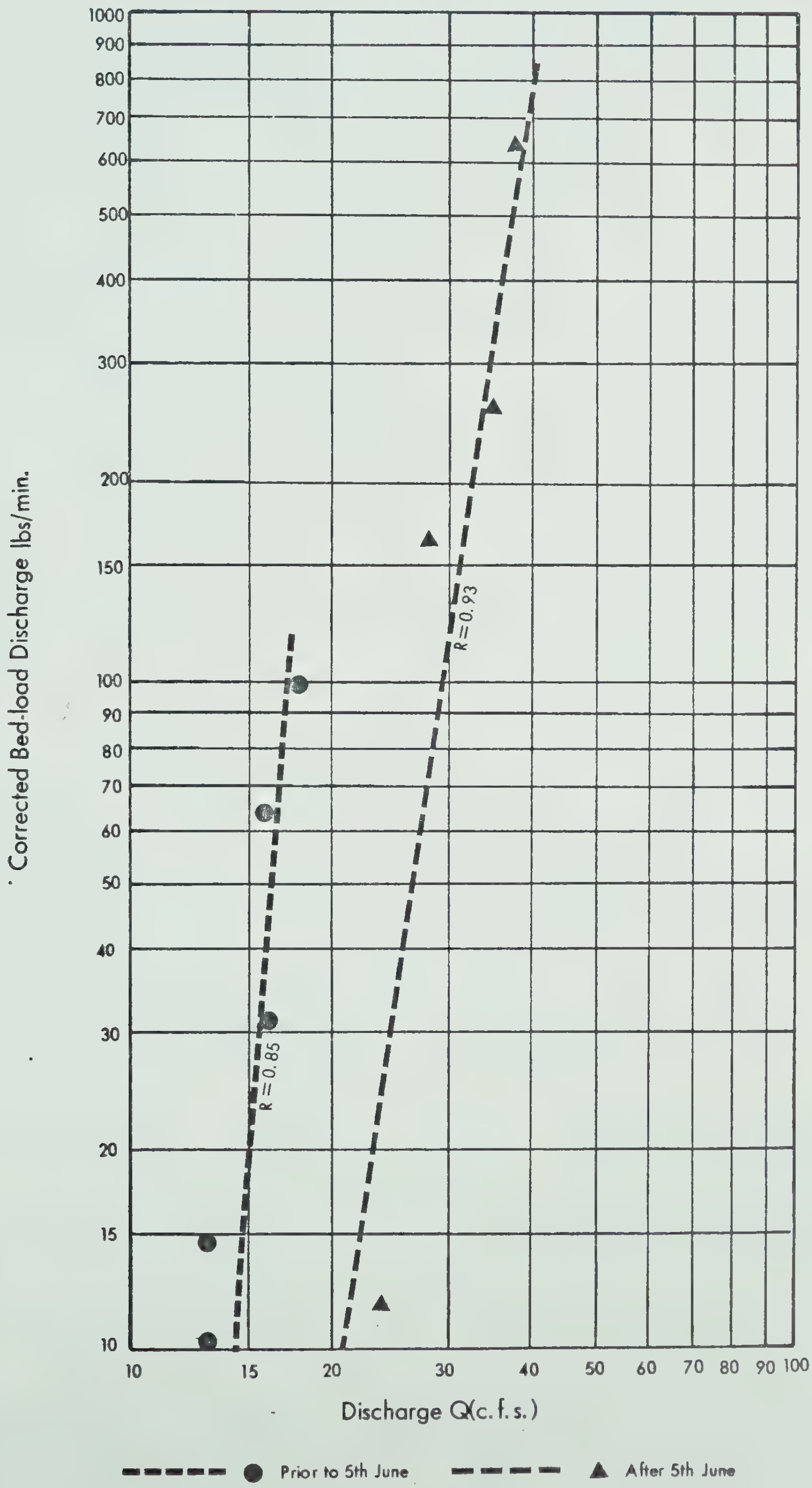
Date	Time	Uncorrected Bed-load lbs./min.	Correction Factor**	Corrected Bed-load Discharge lbs./min.	Stream Discharge c.f.s.
May 26	15.10-15.15	18.75	3.33	62.50	16.0
26	20.25-21.15	29.90	3.33	99.57	17.5
27	17.45-18.30	9.50	3.33	31.63	16.0
28	14.00-16.00	4.50	3.33	14.98	13.0
28	19.20-19.43	3.25	3.33	10.82	14.0
29	15.45-16.41	3.12	3.33	3.12	14.0
30	14.30-15.30	2.00	3.33	2.00	12.0
30	19.00-19.40	2.80	3.33	9.30	14.8
30	19.45-20.22	5.12	3.33	17.05	15.2
31	17.16-18.37	6.15	3.33	20.47	15.0
June 6	14.00-15.10	95.00 LB*	2.93		
		140.00 MS	2.63	647.62	38.0
		0.00 RB	3.33		
6	16.15-16.51	107.50	3.33	257.90	34.0
7	14.20-16.00	48.75	3.33	162.34	28.0
8	15.38-16.30	44.50	3.33	148.18	26.5
9	15.00-16.30	2.00	3.33	6.66	18.5
10	15.00-16.00	0.50	3.33	1.66	16.0
12	18.00-18.30	1.13	3.33	1.13	18.5
22	20.00-20.25	3.50	3.33	11.65	24.0

* LB Left Bank
MS Mid Stream
RB Right Bank

** Corrections based on a straight line relationship between 30 per cent efficiency at a bed-load discharge rate of 20 lbs./min./foot of channel width or less to 50 per cent efficiency at 110 lbs./min./foot of channel width (pers. comm. Gibbs, April 1972).

FIGURE 5.7

CORRECTED BED-LOAD DISCHARGE FROM BASKET SAMPLER MEASUREMENTS BRIDGE CREEK SUMMER 1971



$$G_s = 3.52 \times 10^{-8} Q^{6.45}$$

where R = 0.93 and is significant at the 1% level after the seasonal peak discharge (Figure 5.7.).

5.6. An Explanation for Changes in the Sediment Load Concentration/Water Discharge Ratio in Bridge Creek

From measurements of suspended load concentrations (Section 5.3.) and bed-load concentrations (Section 5.5.) in Bridge Creek, it is evident that in both cases, the sediment concentration/water discharge ratio is less after the peak flow than it is before the peak. The change in the bed-load transport rate appears to be centred around the peak seasonal flow on the 5th of June. Bed-load transported prior to this date required less water discharge than that carried after the 5th of June. In comparison, the suspended load concentration/water discharge ratio appears to decline sequentially as the runoff season progresses. It is possible, however, that the lack of a progressive decline in bed-load transport could be explained as a result of the extreme variability of bed-load transport disguising such a relationship.

There are three possible explanations for why the sediment concentration/water discharge ratio declines. Firstly, a significant rise in water temperature from before the peak flow to after the peak would cause a decrease in the water viscosity and a resulting decrease in the sediment load that a given discharge would be capable of transporting. Changes in temperature are usually related to changes in the fine sediment concentration (see Leliavsky, 1966). Measurements of water temperature given in Table IV.6. show no such change near the seasonal peak flow and therefore a change in fluid viscosity has been discounted.

A second possible explanation, relating especially to bed-load concentration, is a change in the bed pavement or bed armour condition, such that a greater critical discharge is needed after the peak seasonal flow to initiate bed-load transport. Milhous and Klingemann (1971) found for a mountain stream in the Oregon Coastal Range, that the bed-load transport/water discharge ratio increased after a peak flow. The critical water discharge required to initiate bed-load transport prior to the peak flow was 47 c.f.s. but dropped to 29 c.f.s. after the peak. This shift they attributed to a change in the critical discharge required to dislodge

the armour material on the stream bed. The D_{90} of the material they sampled prior to the peak flow was 8.8 cm and decreased to 7.7 cm in the samples taken after the peak.

Kellerhals (1967) found from laboratory observations of bed-armouring that channel pavement formations only occur at low bed-load transport rates. Conversely, at high flows the entire bed becomes active and the pavement no longer exists as a protective layer. A continued period of low flow is then required to winnow away the fines and imbricate the larger particles.

On the basis of these two studies, the possibility that the peak flow in Bridge Creek disrupts an existing bed armour layer has been discounted. If bed armouring was significant in controlling sediment transport prior to the peak flow, then the bed-load concentration/water discharge ratio should have increased after the peak rather than decreased.

During high spring flows, however, selective removal of finer material will probably leave a lag of coarser grain sizes on the stream bed. This would contribute to a decline in the bed-load concentration/water discharge ratio in the latter part of the season.

The third possible explanation for a change in the sediment concentration/water discharge ratio is a change in the rate of sediment supply to the stream. Alpine areas, such as the one occupied by Bridge and Two O'Clock Creeks, can be considered as high energy geomorphic environments, especially during the spring thaw period. This geomorphic activity can be expected to decline later in the summer as freeze thaw cycles and active melt water runoff decline in importance. It is this influence of sediment supply that the writer proposes is most significant in controlling the sediment concentration/water discharge ratio.

5.7. Sediment Supply

The following observations made in Bridge Creek catchment during the field season are used to provide a possible explanation for the decline of the sediment concentration/water discharge ratio as the runoff season progresses.

Bridge Creek catchment has a considerable accumulation of Pleistocene sediments covering its bedrock floor up to an elevation of

approximately 7,000 feet (Plates 2 and 3). With the down cutting of the streams since the Pleistocene, the sediments have been excavated, exposing walls of debris up to 150 feet in height (Plates 11 and 12). These exposures consist largely of glacial till but in one location, this till overlies an older deposit of fluvioglacial material. In most areas, the till is overlain by colluvial deposits up to several tens of feet thick. Except in the upper basin, this colluvial material has now consolidated and forms a shear face on top of the underlying till. Plate 12 shows the complete sequence of these deposits.

The exposures are deeply rilled and gullied into severely eroded hoodoo forms and there is an almost total absence of vegetation. Abundant evidence exists (Plates 13, 14, 15 and 16) to suggest that mud-flows and debris slides carry material off these faces, down the gullied lower slopes, and deposit it in the stream channels. Because these sediments contain grain sizes that range from clays to boulders (Figure 5.8.), this material would supply bed-load and considerable suspended load to the stream. In addition, melt water and rain wash during the spring thaw period probably wash considerable fine material off the basin slopes from extensive areas of frost rived bare ground (Plate 19).

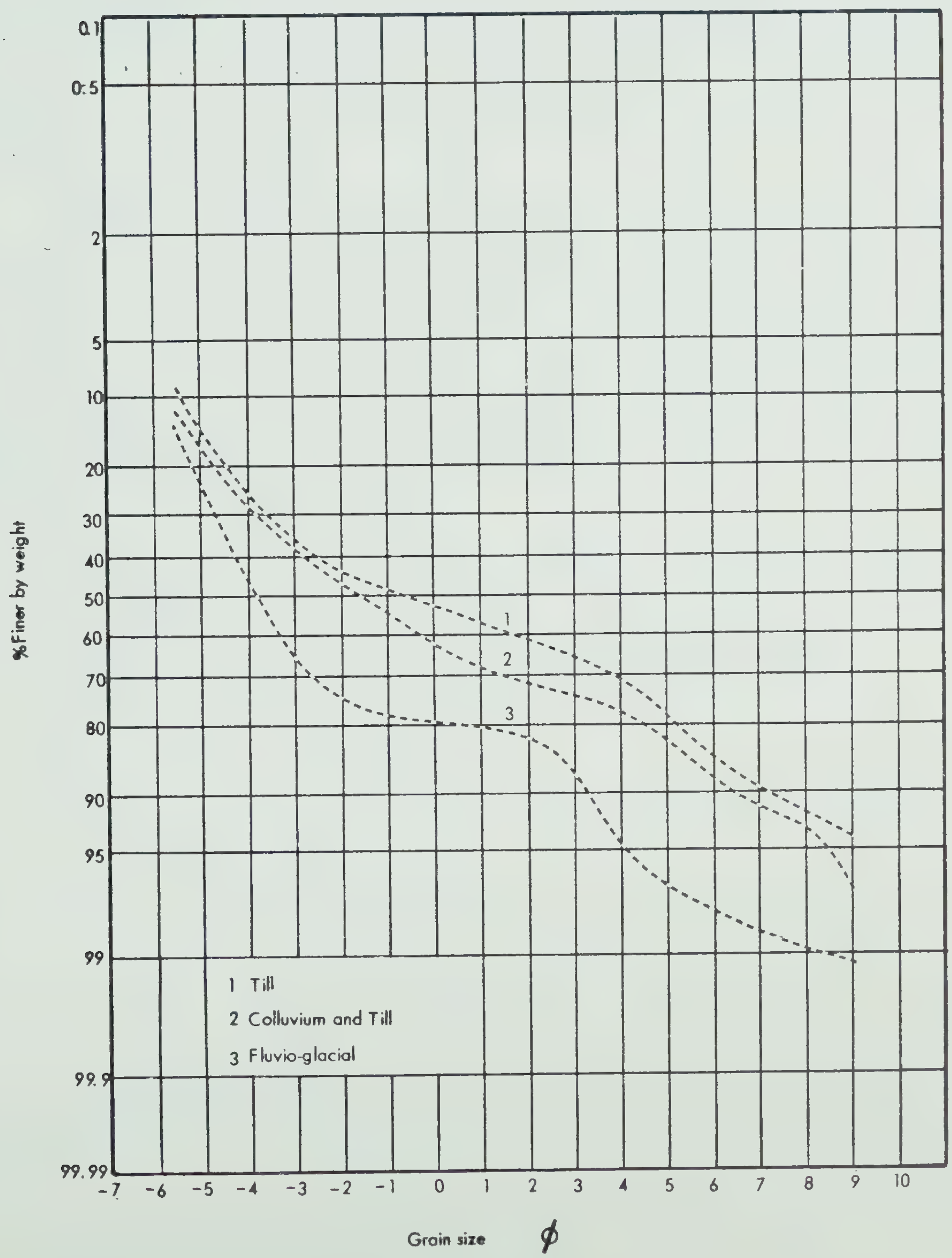
Another source area for sediment supply is in the upper part of the basin. Here material is possibly supplied from scree and solifluction slopes by avalanches and mudflows. Observations in the field above the tree line suggest that these sources are not as significant as the glacial deposits. There are large areas of alpine meadow on the floor of the upper basin with no evidence of recent avalanche or mudflow accumulation. This is not the case at the base of the glacial deposits where nearly all the vegetation shows signs of being recently inundated with debris (Plates 15, 16, 17 and 18).

Despite the lack of quantitative evidence for actual sediment source areas (which would be expensive and take considerable time), observations in the catchment have allowed an estimation to be made as to which areas offer more sediment relative to other areas. As a result the following sequence of events is tentatively suggested.

During the spring thaw in the middle and lower part of the basin, the high banks of glacial debris become saturated with melt water

EXAMPLES OF BRIDGE CREEK ALLUVIAL DEPOSITS

FIGURE5.8



and start to slide and flow down the pre-existing channels excavated during the previous thaw periods. This material accumulates in the channel, probably at a time when water discharge is relatively low (Plates 13 and 14). Up until the time of the peak seasonal discharge from the basin, increasing diurnal fluctuations from the snow fields higher in the catchment provide water for the successive removal of these readily available sediments from within the channel. The heterogeneous nature of these sediments which range in size from boulders down to clays, would provide ample bed-load as well as some suspended load. Suspended load is probably strongly supplemented during the thaw period by sheet and rill erosion of the numerous frost rived bare ground areas (Plate 19) on the basin sides.

With the peak seasonal flow, most of this readily available mass movement debris at the base of the till exposures would be flushed out of the catchment. During later and less significant peak flow periods, only material on the stream bed and some minor bank erosion material would be available for transport. As a result, the transport of sediment for a given water discharge would be less after the seasonal peak flow than it would before the peak.

While this is only one of a number of seasonally cyclic events that could control sediment supply in an alpine basin, the writer believes that it is the most important in the case of Bridge Creek.

CHAPTER VI

CALCULATIONS OF BED-LOAD DISCHARGE USING FORMULAE

6.1. Introduction

Using hydraulic variables measured in the field, the following bed-load formulae have been applied to Bridge and Two O'Clock Creeks for comparison with measured bed-load yields of these streams. A resumé of the formulae is given in Section 2.4. along with the definition of each symbol (these symbols are also given in Appendix A).

Values for grain size are taken from the mean grain size curves for each stream (Figure 5.2.). Width, depth and velocity values are determined from the channel geometry relationships (except where specifically stated otherwise) given in Figures 4.5. and 4.6. at the selected discharge values. Average water temperature during the time which bed-load was being transported was found to be very similar for both streams (43°F). Slope measurements are given in Section 4.5. and the relative density of bed material was measured in the laboratory and found to be 2.66.

The results of each equation for selected discharges are given in tables accompanying the equations in this section and are plotted in Figures 6.1. and 6.2. as bed-load rating curves.

6.2. Calculations based on the Meyer-Peter and Muller Equation

6.2.1. Bridge Creek

The Meyer-Peter and Muller equation can be written as

$$0.25\rho^{1/3}\ g_s'^{2/3} = \gamma_f\ RS\left[\frac{Kb}{Kg}\right]^{3/2} - 0.047\ \gamma_s D_E$$

where in Bridge Creek

$$\rho = \frac{63.325}{32.17} = 1.97$$

$$\gamma_f = 63.325\ \text{lbs/ft}^3$$

$$S = 6.708 \times 10^{-2}$$

$$D_{90} = 0.21$$

$$K_b = \frac{Vm}{R^{2/3}S^{1/2}}$$

$$\gamma_s = (2.66 - 1)\ (63.325) = 105.12$$

$$K_g = \frac{48}{D_{90}^{\ 1/6}} = \frac{1.49}{n'} \qquad \text{where} \qquad n' = 0.031\ D_{90}^{\ 1/6}$$

$$D_{90}^{\ 1/6} = 0.77$$

therefore $K_g = 62.605$

$$D_E = 0.0816 \text{ feet}$$

For Bridge Creek the equation can therefore be written as

$$0.3137\ g_s'^{\,2/3} = 4.248\ R\ [\frac{Kb}{Kg}]^{3/2} - 0.3991$$

The results of this equation for selected discharges are given in Table VI.1.

6.2.2. Two O'Clock Creek

The basic form of this equation is the same as that used in Bridge Creek. In the case of Two O'Clock Creek the distinct variables are:

$$S = 11.4 \times 10^{-2}$$

$$D_E = 0.0564 \text{ ft.}$$

$$D_{90} = 0.1694 \text{ ft.}$$

$$K_g = \frac{48}{D_{90}^{\ 1/6}} = \frac{1.49}{n'} \qquad \text{where} \qquad n' = 0.031\ D_{90}^{\ 1/6}$$

$$D_{90}^{\ 1/6} = 0.7439$$

therefore $K_g = 64.61$

The resulting form of the equation in Two O'Clock Creek can be written as

$$0.3135\ g_s'^{\,2/3} = 7.219\ R[\frac{Kb}{Kg}]^{3/2} - 0.2787$$

The results of this equation for selected discharges are given in Table VI.2.

TABLE VI.1.

COMPUTATIONS OF BED-LOAD DISCHARGE IN BRIDGE CREEK
USING THE MEYER-PETER AND MULLER EQUATION

Q	b_w	A/b_w	V_m	$(A/b_w)^{2/3}$	K_b	$(\frac{K_b}{K_g})^{3/2}$	$4.248R(\frac{K_b}{K_g})^{3/2}$	$0.3137g_s'^{2/3}$	g_s'	g_s	G_s
	ft.		ft/sec.						lbs/ft/sec.	lbs/sec.	lbs/min.
20	9.80	0.70	2.90	0.7883	14.208	0.1080	0.3210	0	0	0	0
25	10.25	0.75	3.30	0.8254	15.442	0.1223	0.3896	0	0	0	0
27	10.45	0.77	3.45	0.8401	15.862	0.1274	0.4166	0.0175	0.0131	0.227	13.62
30	10.55	0.80	3.60	0.8618	16.129	0.1306	0.4437	0.0446	0.7223	12.649	758.94
35	11.00	0.83	3.90	0.8833	17.059	0.1421	0.5010	0.1019	0.8290	15.137	908.22
40	11.50	0.86	4.20	0.9036	17.949	0.1534	0.5603	0.1612	0.8950	17.855	1071.30
60	12.50	0.96	5.20	0.9731	20.635	0.1892	0.7715	0.3724	1.2932	26.834	1610.03

TABLE VI.2.

COMPUTATIONS OF BED-LOAD DISCHARGE IN TWO O'CLOCK CREEK
USING THE MEYER-PETER AND MULLER EQUATION

Q	b_w	A/b_w	Vm	$(A/b_w)^{2/3}$	K_b	$\left(\frac{K_b}{K_g}\right)^{3/2}$	$7.219R\left(\frac{K_b}{K_g}\right)^{3/2}$	$0.3137{g'_s}^{2/3}$	g'_s	g_s	G_s
	ft.		ft/sec.						lbs/ft/sec.	lbs/sec.	lbs/min.
10	10.0	0.40	2.40	0.5429	13.094	0.0912	0.2635	0	0	0	0
15	11.0	0.45	2.80	0.5872	14.125	0.1022	0.3319	0.0532	0.0642	1.17	70.33
20	11.8	0.55	2.90	0.6708	12.800	0.0882	0.3503	0.0716	0.1091	2.13	128.10
25	12.5	0.65	3.00	0.7504	11.840	0.0784	0.3681	0.0894	0.1523	3.16	189.61
30	13.0	0.74	3.05	0.8181	11.043	0.0707	0.3774	0.0987	0.1766	3.81	228.66
35	13.6	0.83	3.10	0.8833	10.396	0.0645	0.3866	0.1079	0.2019	4.56	273.48
40	14.0	0.90	3.20	0.9322	10.168	0.0624	0.4055	0.1268	0.2572	5.98	358.64

6.3. Calculations of Bed-load based on the Schoklitsch (1934) Formula

6.3.1. Bridge Creek

This formula is usually written in the form

$$G_1 = 25 \frac{S^{2/3}}{D_E^{1/2}} (Q_1 - Q_{01})$$

Because the Schoklitsch method for determining critical discharge proved to be unreliable, values of 10 c.f.s. and 18 c.f.s. were selected from basket sampler measurements (Figure 5.6.). The effective grain size (D_E) is calculated for a known discharge (35 c.f.s.) and these results are shown in Table VI.3. This value of G_1 was then applied in the Schoklitsch formula with a known slope. D_E is therefore determined as 0.1272 and $D_E^{1/2} = 0.357$.

The resultant form of the equation for Bridge Creek is

$$G_1 = 1.217 (Q_1 - Q_{01})$$

The results of bed-load discharge calculated using this equation for selected discharges are given in Tables VI.4a and VI.4b.

6.3.2. Two O'Clock Creek

The basic form of the equation is the same as that used for Bridge Creek. The effective grain size D_E has been calculated using a discharge of 35 c.f.s. in the same manner as that used in the Bridge Creek calculations, arriving at a value of $D_E = 0.09$ and $D_E^{1/2} = 0.30$.

The resulting form of the equation for Two O'Clock Creek is

$$G_1 = 3.2 (Q - Q_{01})$$

The results of bed-load calculations for particular discharges are shown in Table VI.5.

TABLE VI.3.

CALCULATION OF EFFECTIVE GRAIN SIZE
FOR THE SCHOKLITSCH FORMULA - BRIDGE CREEK

Calculated for a discharge of 35 c.f.s.
using a critical discharge of 15 c.f.s.

D feet	D mean	%	$25 \frac{S^{2/3}}{D_E^{1/2}}$	(Q_1-Q_{01})	G_s
0.3958-0.2166	0.3062	10	0.7852	1.666	0.1309
0.2166-0.1333	0.1749	20	1.0389	1.666	0.3462
0.1333-0.0816	0.1074	20	1.3259	1.666	0.4417
0.0816-0.0583	0.0699	10	1.6439	1.666	0.2739
0.0583-0.0316	0.0449	10	2.0514	1.666	0.3419
0.0316-0.0116	0.0216	10	2.9577	1.666	0.4927
					2.0273

TABLE VI.4a

COMPUTATIONS OF BED-LOAD DISCHARGE
USING THE SCHOKLITSCH (1934) FORMULA FOR BRIDGE CREEK

Critical discharge 10 c.f.s.

Q	(Q_1-Q_{01}) c.f.s.	G_1 lbs/sec/ft.	G_2 lbs/sec.	b_w feet	G_s lbs/min.
10	0	0	0	8.3	0
13	0.341	0.415	3.654	8.8	219.05
15	0.555	0.675	6.079	9.0	364.73
17	0.753	0.916	8.519	9.3	511.13
20	1.020	1.242	12.170	9.8	730.19
25	1.429	1.739	18.255	10.5	1095.30
30	1.786	2.173	24.340	11.2	1460.40

TABLE VI.4b

COMPUTATIONS OF BED-LOAD DISCHARGE
USING THE SCHOKLITSCH (1934) FORMULA FOR BRIDGE CREEK

Critical discharge 18 c.f.s.

Q	(Q_1-Q_{01}) c.f.s.	G_1 lbs/sec/ft.	G_2 lbs/sec.	b_w feet	G_s lbs/min.
18	0	0	0	9.4	0
20	0.204	0.248	2.434	9.8	146.04
23	0.490	0.596	6.085	10.2	365.09
25	0.666	0.811	8.519	10.5	511.13
27	0.833	1.014	10.950	10.8	657.17
30	1.071	1.304	14.600	11.2	876.23
35	1.478	1.799	20.689	11.5	1241.37

TABLE VI.5.

CALCULATIONS OF BED-LOAD DISCHARGE FOR
TWO O'CLOCK CREEK USING THE SCHOKLITSCH (1934) FORMULA

Q	(Q_1-Q_{01}) c.f.s.	G_1 lbs/sec/ft.	G_2 lbs/sec.	b_w feet	G_s lbs/min.
10	0	0	0	10.0	0
15	0	0	0	11.0	0
20	0.423	1.354	15.97	11.8	958.34
25	0.800	2.650	32.00	12.5	1920.00
30	1.153	3.690	47.96	13.0	2877.89
35	1.470	4.704	63.97	13.6	3838.46
40	1.785	5.712	79.96	14.0	4798.00

6.4. Calculations of Bed-load Discharge using the Blench 1969 Regime Slope Equation

The recommended form of the equation is

$$f'''_{(c)} = \frac{S\ K\ b^{1/6}\ Q^{1/12}}{k\ F_{bo}^{11/12}}$$

where $K = \dfrac{3.63g}{\nu^{1/4}}$

$\nu = 1.58 \times 10^{-5}$

therefore $K = 1852.39$

The meander correction coefficient (k) is applied to take into account that portion of the energy slope dissipated through the curvature of flow and by irregular bed forms. Blench states that this ranges from 1.25 to 2.75 in natural rivers and for the purposes of this study the maximum value of 2.75 was selected because of the twisting, plunging channel form over the study reach in both streams.

$F_{bo} \simeq F_b = \frac{Vm^2}{d}$ at velocity conditions where there is little or no bed-load discharge. For both streams, the discharge value of 15 c.f.s. is selected to represent this condition and velocity is interpreted from the bed-load and discharge (Q) relationships shown in Figures 5.5. and 5.6. The resulting bed-load rating curve shown in Figure 6.1. is evidence that further refinement of the Blench bed-load formula in Bridge Creek based on a varying critical entrainment velocity, would not significantly increase the accuracy of the calculated bed-load discharges.

The values for bed-load charge are taken from Blench's Figure 7.2. (1969) which plots $f'''_{(c)}$ vs C in parts per one hundred thousand from the equation

$$f'''_{(c)} = \frac{(1 + 0.12\ C)^{11/12}}{1 + C/233}$$

The charge is then converted to pounds per minute.

6.4.1. Bridge Creek

$$\text{Critical velocity} = 2.5$$
$$d = 0.65$$
$$F_{bo} = 9.615$$
$$S = 0.067$$

The resulting form of the equation for use in Bridge Creek is

$$f'''_{(c)} = \frac{0.067 \times 1852.4 \times b^{1/6}\ Q^{1/12}}{2.75 \times 7.962}$$

$$= 5.668 \times b^{1/6}\ Q^{1/12}$$

Bed-load charge is calculated using this equation and the results are presented in Table VI.6.

6.4.2. Two O'Clock Creek

The basic form of the equation remains the same as that used in Bridge Creek. Variables peculiar to Two O'Clock Creek are:

$$S = 0.114$$
$$F_{bo} = 17.23$$
$$d = 0.45$$
$$\text{Critical velocity} = 2.78$$

The resulting form of the Blench regime slope equation for Two O'Clock Creek is

$$f'''_{(c)} = \frac{0.114 \times 1852.39 \times b^{1/6}\ Q^{1/12}}{2.75 \times 13.58}$$

$$= 5.655\ b^{1/6}\ Q^{1/12}$$

Calculations of bed-load charge using this equation are presented in Table VI.7.

6.5. Calculations of Bed-load Discharge using the Modified Einstein Procedure of Colby and Hubbell 1961

The first step in computing the bed-load discharge using the modified Einstein procedure is the solution of the equation

TABLE VI.6.

CALCULATIONS OF BED-LOAD DISCHARGE FOR BRIDGE CREEK USING THE BLENCH (1969) REGIME SLOPE EQUATION

Q c.f.s.	$Q^{1/12}$	b feet	$b^{1/6}$	$f'''_{(c)}$	C parts/100,000	G_s lbs/min.
10	1.211	8.40	1.1426	7.853	118	68.0
15	1.253	9.20	1.1447	8.140	124	78.0
20	1.283	9.80	1.1463	8.346	126	95.7
25	1.308	10.02	1.1469	8.514	128	119.7
30	1.327	10.52	1.1480	8.646	130	148.2
35	1.345	11.00	1.1491	8.771	132	175.5
40	1.360	11.50	1.1503	8.878	134	203.6

TABLE VI.7.

CALCULATIONS OF BED-LOAD DISCHARGE FOR TWO O'CLOCK CREEK USING THE BLENCH (1969) REGIME SLOPE EQUATION

Q c.f.s.	$Q^{1/12}$	b feet	$b^{1/6}$	$f'''_{(c)}$	C parts/100,000	G_s lbs/min.
10	1.210	10.0	1.1468	7.8540	110	41.8
15	1.253	11.0	1.1491	8.1427	122	70.1
20	1.283	11.8	1.1509	8.3507	126	95.7
25	1.308	12.5	1.1524	8.5245	128	119.7
30	1.327	13.0	1.1533	8.6552	130	148.2
35	1.345	13.6	1.1545	8.7820	132	175.5
40	1.360	14.0	1.1552	8.8850	134	203.6

TABLE VI.8.

SAMPLE CALCULATION USING THE MODIFIED EINSTEIN PROCEDURE ON BRIDGE CREEK

Discharge 35 c.f.s. $(RS)_m$ 0.00394

Size Range feet	i_b %	D_g feet	$D_g^{3/2}$	Ψ_m	$\Phi*$	$i_b \Phi* D_g^{3/2}$ x10^6
0.3958-0.2166	10	0.2928	0.1584	49.34	-	-
0.2166-0.1670	10	0.1902	0.0829	32.22	-	-
0.1670-0.1500	10	0.1583	0.0630	26.68	-	-
0.1500-0.1067	10	0.1284	0.0460	21.64	0.0016	7.36
0.1067-0.0817	10	0.1167	0.0398	19.66	0.0035	13.95
0.0817-0.0583	10	0.0690	0.0181	19.38	0.0038	6.88
0.0583-0.0316	10	0.4429	0.0088	19.38	0.0038	3.35
0.0316-0.0116	10	0.0191	0.0025	19.38	0.0038	0.93
						32.47

TABLE VI.9.

BED-LOAD DISCHARGE CALCULATIONS ON BRIDGE CREEK USING THE MODIFIED EINSTEIN PROCEDURE

Q c.f.s.	d feet	Vm f.p.s.	$\frac{xd}{k_s}$	$\sqrt{(RS)_m}$	$(RS)_m$	$i_b \Phi* D_g^{3/2}$ x10^6	b_w feet	G_s lbs/min.
15	0.66	2.5	5.500	0.0425	0.001806	-	9.20	-
20	0.70	2.9	5.830	0.0487	0.002371	-	9.80	-
25	0.75	3.3	6.250	0.0544	0.002959	1.804	10.25	0.664
30	0.80	3.6	6.667	0.0585	0.003422	8.951	10.55	3.399
35	0.83	3.9	6.917	0.0628	0.003943	32.470	11.00	12.858
40	0.86	4.2	7.167	0.0671	0.004500	80.769	11.50	33.488
50	0.92	4.7	7.667	0.0734	0.005387	245.030	12.00	105.853

TABLE VI.10.

SAMPLE CALCULATION USING THE MODIFIED EINSTEIN PROCEDURE ON TWO O'CLOCK CREEK

Discharge 35 c.f.s. (RS) 0.002266

Size Range feet	i_b %	D_g feet	$D_g^{3/2}$	Ψ_m	$\Phi*$	$i_b \Phi* D_g^{3/2}$ x10^6
0.2694-0.1694	10	0.2136	0.0987	62.570	-	-
0.1694-0.1361	10	0.1518	0.0591	44.480	-	-
0.1361-0.1033	10	0.1185	0.0408	34.686	-	-
0.1033-0.0800	10	0.0919	0.0274	26.637	0.00012	0.328
0.0800-0.0564	10	0.0671	0.0174	19.638	0.00350	6.090
0.0564-0.0322	10	0.0425	0.0088	19.047	0.00480	4.205
0.0322-0.0219	10	0.0264	0.0043	19.047	0.00480	2.064
0.0219-0.0113	10	0.0155	0.0019	19.047	0.00480	0.912
						13.600

TABLE VI.11.

BED-LOAD DISCHARGE CALCULATIONS ON TWO O'CLOCK CREEK USING THE MODIFIED EINSTEIN PROCEDURE

Q c.f.s.	d feet	Vm f.p.s.	$\frac{xd}{k_s}$	$\sqrt{(RS)_m}$	$(RS)_m$	$i_b \Phi* D_g^{3/2}$ x10^6	b_w feet	G_s lbs/min.
10	0.40	2.40	4.44	0.0428	0.000183	1.479	10.0	0.532
15	0.46	2.80	5.11	0.0482	0.002266	13.600	11.0	5.386
20	0.56	2.90	6.22	0.0476	0.002266	13.600	11.8	5.770
25	0.65	3.00	7.22	0.0476	0.002266	13.600	12.5	6.112
30	0.72	3.05	8.00	0.0475	0.002266	13.600	13.0	6.357
35	0.83	3.15	9.22	0.0475	0.002266	13.600	13.6	6.650
40	0.90	3.20	10.00	0.0475	0.002266	13.600	14.0	6.846

$$\sqrt{(RS)}_m = Vm / 32.6 \log_{10} (12.27xd/k_s)$$

The trial-and-error solution of this equation can be made graphically from Plate 1 (Colby and Hubbell, 1961). The roughness diameter (k_s) is that particle size of bed material for which 65 per cent by weight is finer (D_{65}). k_s is equal to 0.12 feet in Bridge Creek and 0.09 feet in Two O'Clock Creek. By trial and error, the dimensionless parameter x is determined for both Bridge and Two O'Clock Creeks from Plate 1 to be equal to one in both cases. To determine x, a value of $\nu = 1.58 \times 10^{-5}$ corresponding to a water temperature of 43°F is used. From the values of xd/k_s and the mean velocities (Vm) from Figures 4.5. and 4.6., the values of $\sqrt{(RS)}_m$ are determined from Plate 1 (Colby and Hubbell, 1961). The remainder of the procedure is outlined in Section 2.4.4. Table VI.8. shows the calculations undertaken to determine the transport function at one stage for the range of grain sizes present in Bridge Creek. The same is shown in Table VI.10. for Two O'Clock Creek. Material finer than 0.011 feet is not included in the analysis. As can be seen in Tables VI.8. and VI.10., this fine material contributes very little to the calculated bed-load discharge. Calculations for bed-load discharge using the Modified Einstein equation are shown in Tables VI.9. for Bridge Creek and Table VI.11. for Two O'Clock Creek.

Because the results of this calculation are to be compared to the measurements of material moving as bed-load, the determination of the suspended load of particle sizes for which the bed-load function exists has not been included. It is assumed that material in suspension will pass through the weirs except possibly at low flows, when some of it may contribute to the fine material caught in the pools.

6.6. A Comparison of Bed-load Formula Results

The results of the four bed-load formulae used in each stream are plotted in Figures 6.1. and 6.2. for comparison with measured bed-load discharge. Briefly stated, these results show a wide range of estimates and therefore the formulae are unreliable for use in this situation.

The Meyer-Peter and Muller (1948) equation appears to over-

estimate bed-load discharge at low water discharges in Two O'Clock Creek. The experimental range of this formula more closely conforms with the two streams studied than any of the other formulae used. An interesting aspect is the accuracy of the bed shear stress calculated by the formula (0.047 γ_s D_m) corresponding to the start of bed-load movement in Two O'Clock Creek. This value is too high for Bridge Creek where bed-load starts to move at a lower value (10 or 18 c.f.s.) than that calculated (27 c.f.s.).

The Schoklitsch 1934 formula gives the highest estimation of bed-load yield of any formula applied in either Bridge or Two O'Clock Creeks, despite the application of an observed value for critical discharge rather than Schoklitsch's computed value. It appears that this formula is over-influenced by slope, which admittedly is excessive and outside the experimental range of the equation. In addition the effective grain size diameter may be intended as a measure of roughness as well as the availability of sediment for transport. Roughness in these mountain streams is not well represented by bulk samples of transported bed-load but is more a factor of the larger blocks over which the water plunges in a series of small cataracts.

The results of the Blench formula suggest lower increases in bed-load discharge with increasing water discharge than field measurements show. The formula does not take into account the decreased proportion of energy required to overcome the channel irregularities (a roughness factor) with increased stage such as the other methods do. This method would therefore be more accurate if the meander correction coefficient decreased inversely with stage (Hollingshead, 1968).

The Modified Einstein equation results plot very low on both graphs (Figures 6.1. and 6.2.). This probably reflects the dependence of this formula on measured mean velocity, a variable that is difficult to describe in such small streams. Evidence from field measurements of velocity showed that as discharge increased, the bank turbulence caused a decrease in velocity near the banks, such that the flow was directed very rapidly down the centre of the channel. At low flows the velocities measured were lower but more constant across the width of the stream even up to within several inches of either bank. The result is that

mean velocity calculations made at high discharges from width and depth measurements are low compared to the velocities that actually entrain bed-material. Probably the best way of compensating for this error in small streams with rough boundaries is to take accurate velocity measurements at three or four representative cross-sections and to calculate bed-load discharge only for the width of channel where bed-load is known to be moving. This may entail visual or acoustic observations of bed-load movement to determine critical velocities and the width of the mobile portion of the bed.

In conclusion, the bed-load formula results suggest that this method of estimation is unsatisfactory for predicting bed-load discharge in small mountain streams. The conditions in the small, rough boundary steep streams are so different from the experimental conditions for which the formulae were derived that any relationship is unlikely. In this geomorphic environment, bed-load is not controlled solely by hydraulic conditions, but also by supply and probably varying conditions of critical tractive force (Milhous and Klingeman , 1971) required to entrain particles. As a result, it appears that some method of direct bed-load measurement is the only reasonably accurate technique available for determining bed-load discharge in small mountain streams.

FIGURE 6.1

BED-LOAD DISCHARGE RATING CURVES
BRIDGE CREEK 1971

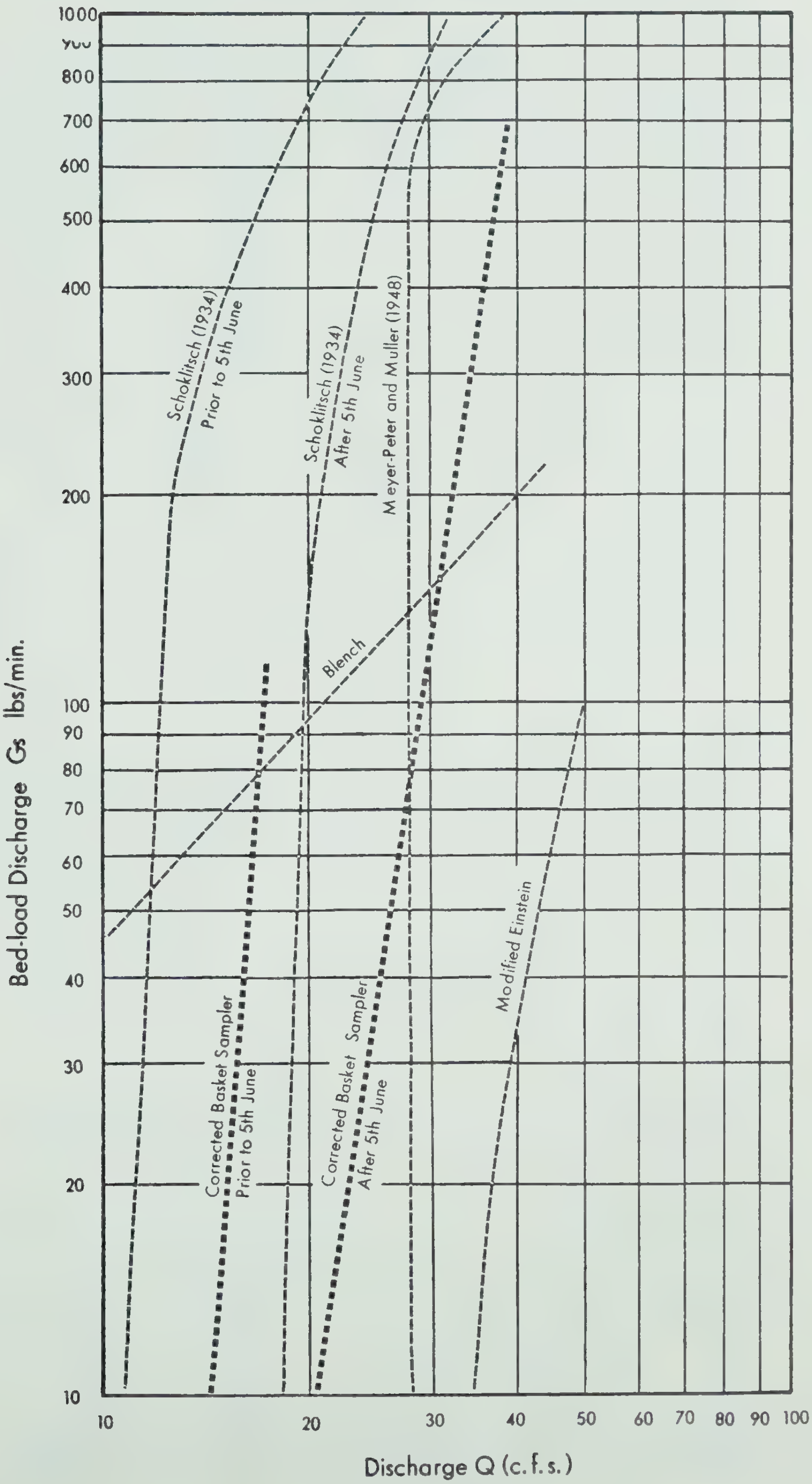
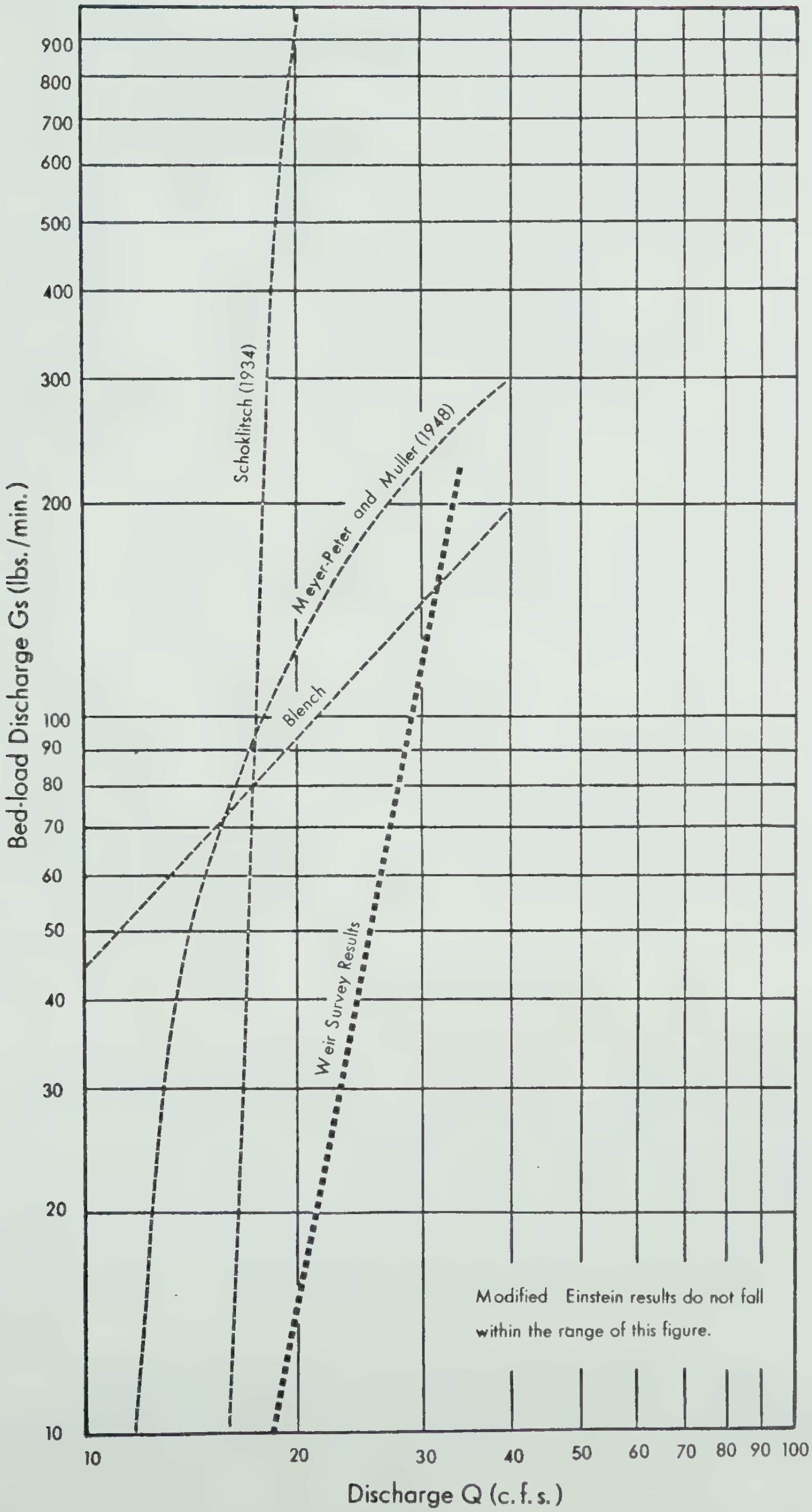


FIGURE 6.2

BED-LOAD DISCHARGE RATING CURVES

TWO O'CLOCK CREEK 1971



CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

Climatic data and runoff measurements from Two O'Clock and Bridge Creeks during 1971, show a very close correspondence between air temperature and resulting snow melt discharge for the early part of the runoff season. This relationship was described for Two O'Clock Creek by McPherson (1971) for the summer of 1969. The seasonal peak flow of 1971 on Bridge Creek, however, shows the importance of rainfall on the winter snow pack. This was also observed for a secondary flood in Two O'Clock Creek by McPherson in 1969. Rainfall late in the season does not appear to significantly affect stream discharge. Further evidence for this was the storm (1.75 inches of rainfall) recorded by McPherson (1971) in Two O'Clock Creek basin in August 1969. This intense rainstorm produced only a minor increase in water and sediment discharge.

For Two O'Clock Creek, the weir sedimentation method of measuring bed-load accumulation proved to be a suitable technique for establishing a bed-load rating curve. A close relationship exists between bed-load discharge and water discharge in this stream. A generalized bed-load rating curve has been determined from the weir survey data on Two O'Clock Creek and has the form:

$$G_s = aQ^{5.0}$$

Due to the collapse of the weir on Bridge Creek, insufficient measurements of sediment accumulation were made to construct a bed-load rating curve from the weir survey data. Three weir survey results were obtained and these are compared with the basket sampler measurements on this stream. This enabled tentative basket sampler efficiencies to be described.

The basket sampler results from Bridge Creek show that this technique, when used in a small mountain stream, is a dependable method

for determining the bed-load transport pattern. In Bridge Creek, the two bed-load rating curves constructed from basket sampling data show a close relationship between water discharge and bed-load discharge. An inherent difficulty with basket sampling, however, is the determination of a hydraulic efficiency for the sampler.

Tentative efficiencies were determined for the basket sampler used in Bridge Creek. The amount of bed-load caught in the weir between each survey was compared with the bed-load value calculated from the basket sampler rating curves, for the same period of time. On this basis the sampler efficiencies ranged from 25 per cent at low discharges to 75 per cent at higher discharges. Because only three comparisons were made between weir survey results and basket sampler results, these efficiency estimations are limited in their reliability. What is interesting is the trend of increasing sampler efficiency with increasing water and sediment discharge. This trend has also been observed by Samide (1971) for larger rivers and by C. Gibbs (pers. comm., 1972) for a laboratory flume. The results from C. Gibbs are used to determine the corrected basket sampler rating curves for Bridge Creek using percentage efficiencies that range from 25 per cent at bed-load charges of 20 lbs./min./foot to 50 per cent at bed-load discharges of 110 lbs./min./foot.

The bed-load sampling results from Bridge Creek show that the sediment concentration/water discharge ratio declined from relatively high values prior to the seasonal peak flow to lower values after the peak. For this reason, two separate bed-load rating curves have been used for this stream. Milhous and Klingemann (1971) found that in a stream in the Oregon Coastal Range, the bed-load concentration/water discharge ratio increased after the peak flow which is in opposition to the results obtained on Bridge Creek. This increase in bed-load discharge after the peak, Milhous and Klingemann accounted for as a result of the disruption of the bed-armour condition of the bed during the peak flow, resulting in a subsequent decrease in the critical discharge required to entrain bed-material. In Bridge Creek, the critical discharge required to entrain bed-load increased after the peak flow, discounting the possibility of bed-armour significantly controlling bed-load transport early in the season.

The corrected basket sampler bed-load rating curves can be

described by the following generalized linear relationships:

$$G_s = b\ Q^{6.8} \text{ prior to the peak flow}$$

and

$$G_s = c\ Q^{6.5} \text{ after the peak flow}$$

A similar decline in the sediment concentration/water discharge ratio was observed from suspended sediment sample measurements taken in Bridge Creek. This ratio declined as the runoff season proceeded. A step-up multiple regression analysis determined that water discharge accounted for 15.4 per cent of the variance in the water discharge - suspended load relationship. If the day the sample was taken on is also included in the analysis, a total of 23.5 per cent of the variance is accounted for, showing that the suspended sediment concentration is partially dependent on whether the sample was taken early in the runoff season or later in the season. The effect of rising and falling stage on suspended sediment was shown to be insignificant in Bridge Creek.

This change in the suspended sediment concentration/water discharge ratio has been observed by Hall (1967) in the Tyne River in England and also by Brown (1972) in south eastern New South Wales, Australia. These two researchers used separate summer and winter suspended sediment rating curves due to variations in sediment supply.

Qualitative field observations suggest that sediment supply is the major factor causing a decrease in both suspended-load and bed-load concentration/water discharge ratios. High banks of glacial till and colluvial debris marginal to Bridge Creek channel below an altitude of 7,000 feet appear to supply a large proportion of the stream's sediment load. During the spring thaw this material slides and flows off these steep faces and is deposited in the stream channel. During the spring thaw and early summer period, snow melt and rainwash probably carry considerable amounts of fine material off the basin slopes from extensive areas of frost rived bare ground. Later in the summer, with a decrease in the intensity of geomorphic processes in the basin, the possible formation of a stream bed pavement, and the removal of nearly all the available mass movement debris from the stream channel by the peak flow, sediment load carried by the stream may be expected to

decline.

The application of existing bed-load formulae in small mountain streams appears to be subject to considerable error. Of the four formulae used (Blench regime equation, Meyer-Peter and Muller 1948 equation, Schoklitsch 1934 equation and the Modified Einstein, Colby and Hubbell 1961 equation), none gave an accurate estimation of bed-load discharge. If the evidence for sediment supply partially controlling bed-load transport is accepted, then it is not unexpected that these formulae do not accurately predict bed-load discharge. These formulae rely on hydraulic and sediment parameters measured in the channel and not on catchment characteristics.

As a result of these bed-load formulae applications, it is suggested that some method of direct measurement will result in a more accurate estimation of bed-load yield in mountain streams.

7.2. Recommendations

An improvement to the weir sedimentation technique would be the mechanical analysis of suspended load. This would determine more accurately what proportion of the material caught in the weir is the result of suspended sedimentation.

In future weir sedimentation studies it is recommended that during construction, a gate is included in the front of the weir. This would enable the flushing out of accumulated sediment at periods throughout the runoff season in readiness for further deposition.

A problem always present with the weir sedimentation method is the possibility of a peak flow bypassing or collapsing the weir. This can be guarded against by the careful selection of a weir site and by an adequate method of removing accumulated sediment from behind.

Bed-load sampling is the simplest direct method of measuring bed-load discharge and is not subject to failure during exceptionally high flows in a small stream. Further work using samplers in similar fluviomorphic environments will probably result in more accurate estimations of sampler hydraulic efficiency and loss of fines.

The sampler is a mobile instrument and does not require constant maintenance throughout the study period. It is also sensitive

to minor bed-load fluctuations and is therefore useful in the study of bed-load transport patterns as well as the determination of the critical discharges required to initiate bed-load transport.

An additional problem associated with the use of bed-load samplers is the variability of bed-load discharge over a short period of time. This means that numerous samples must be taken over any one sampling period to determine the average transport rate for a particular discharge.

Because of the relative simplicity of bed-load sampling and its sensitivity to changes in bed-load transport, it is recommended that this technique be used in future studies in mountain streams.

If bed-load formulae are to be pursued further for estimating bed-load yield from mountain streams, the following recommendations are made. Future studies should use average velocity measurements from three or four cross-sections rather than estimated velocity from channel geometry measurements. Also, some estimations of the width of moving bed-material should be made rather than using average channel width. Similarly, the depth of flow over the moving bed-material rather than the average cross-sectional depth would possibly improve many of the bed-load estimations.

The determination of the discharge critical for the transport of bed-material is realized to be an important parameter and should always be included in field investigations.

From the results of weir sedimentation and basket sampler measurements it is possible to construct simple bed-load discharge, water discharge relationships. In future work it may be possible to determine if there is any general similarity in the shape and the slope of these rating curves for a number of alpine streams. Because only relatively low bed-load transport rates were measured in both Bridge and Two O'Clock Creeks, it is realized that the relationships determined between bed-load discharge and water discharge probably do not exist at higher flows. Further research at higher stream discharges is required to determine the shape of the curves under these conditions.

Due to the dependency of sediment concentration on sediment

supply in Bridge Creek, it is apparent that a single suspended sediment or bed-load rating curve would be unsatisfactory for predicting sediment yield. It is therefore recommended that accurate sediment yield studies in small alpine watersheds may have to be based on the use of several sediment rating curves representing different conditions at different periods throughout the runoff season.

It is possible that future studies in alpine streams will show that the importance of sediment supply in influencing bed-load and suspended load transport is not unique to Bridge Creek. These studies might look in quantitative detail at factors affecting sediment supply to stream channels in order to improve on qualitative proposals made in this study. Such an analysis,along with more detailed studies of water temperature, rising and falling stage and bed-armouring, could help to further explain the very large variance associated with sediment rating curves in so many streams.

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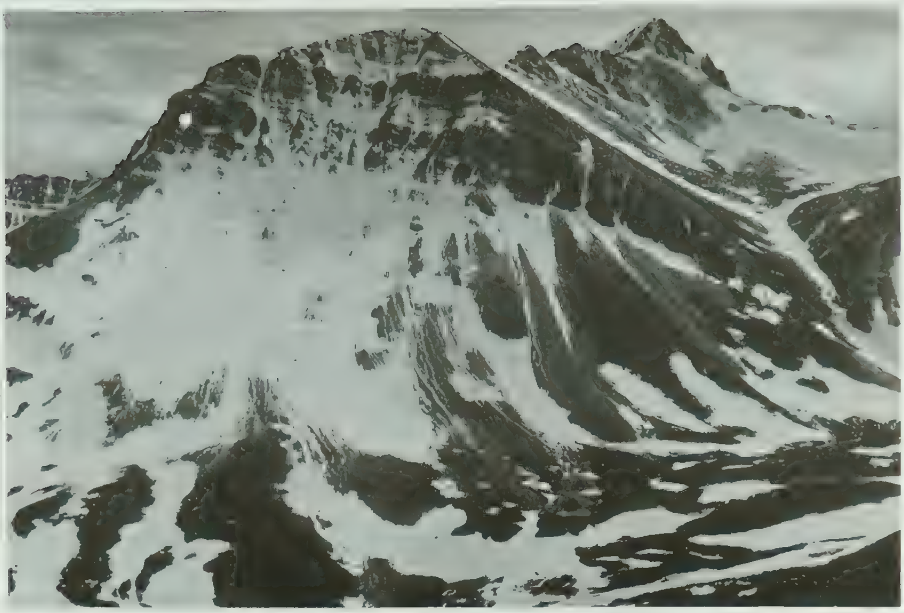

Plate 1

North facing slope in the upper part of Two O'Clock Creek basin. Mid June, 1971.

Plate 2

South tributary of Bridge Creek showing stream excavation of glacial and colluvial debris on basin floor. Mid June, 1971.

Plate 3

North tributaries of Bridge Creek showing stream excavation of the glacial and colluvial debris. Mid June, 1971.

Plate 4

Severely eroded bedrock in the most northerly portion of Bridge Creek catchment. Mid June, 1971.

Plate 5

Bridge Creek weir.

Plate 6

Bridge Creek weir from the left bank, upstream.

Plate 7

Front of Two O'Clock Creek weir.

Plate 8

Water level recorder at the first recording site used on Bridge Creek. A diurnal peak can be seen on the trace.

Plate 9

Basket sampler and second water level recorder site on Bridge Creek.

Plate 10

Half size basket sampler (12x6x15 ins) with quarter inch mesh.

Plate 11

Stream eroded till deposit
in the lower part of
Bridge Creek basin.

Plate 12

Stream eroded stratigraphic
sequence of sedimentary
deposits in Bridge Creek basin:

1. Colluvial material
2. Till
3. Fluvio-glacial material.

Plate 13

Mass movement debris in Bridge Creek stream channel at the base of the till face shown in Plate 11. Prior to the seasonal peak flow, 1972.

Plate 14

Heterogeneous mixture of the mass movement debris. Note the displacement of the stream channel around the toe of the feature. Prior to the seasonal peak flow, 1972.

Plate 15

Inundated vegetation at the base of the till face shown in Plate 11.

Plate 16

Spring thaw mudflow deposits caught in the lower branches of a tree at the base of the deposits shown in Plate 12.

Plate 17

Old mass movement debris that has slid down from the face shown in Plate 11 (behind the camera), crossing the stream and covering the opposite stream bank. Subsequent stream erosion has excavated this section. Note the paleosol between the two deposits.

Plate 18

Small debris flow channels at the base of till face shown in Plate 12.

Plate 19

Frost rived bare ground near the weir site in Bridge Creek basin.

Plate 20

A point where the Bridge Creek entrains bedrock debris. The lower part of the slope has been swept clean by higher flows.

Plate 21


N
Bed-load Sampler
Weir
BRIDGE CREEK CATCHMENT
Uncontrolled Aerial Mozaic
0
miles
1
North Saskatchewan River

APPENDIX A

SYMBOLS

Symbol	Meaning
b	Channel breadth, general
b_w	Water surface breadth
C	Bed-load charge
C_s	Suspended sediment concentration
D_E	Effective grain size
D_g	Geometric grain size
D_x	The specific grain size at which x per cent of the total sample weight is smaller than
D	Blench's mean grain size
d	Shield's mean grain size
d	Mean depth of flow
F_b	Blench's bed factor V^2/d
F_{bo}	Zero bed factor
G_1	Bed-load discharge, lbs., per foot, per second, dry weight (Schoklitsch)
G_2	Bed-load discharge, lbs. per second dry weight (Schoklitsch)
G_s	Bed-load discharge, dry weight
g	Gravitational acceleration
g_s	Sediment discharge per unit width dry weight
$g's$	Sediment discharge per unit width, submerged weight
i_b	Fraction of specified size range of total bed sample by weight
k	Meander correction coefficient in regime slope equation
k_s	Equivalent sand grain roughness
K_b	Strickler roughness coefficient
K_g	Particle grain roughness
M	du Boys material parameter which is a function of the slope and the particle size
p	Wetted perimeter of the channel
Q_1	Stream discharge per unit width (Schoklitsch)
Q_{01}	Critical stream discharge per unit width (Schoklitsch)
Q_B	That discharge which acts on the stream bed only
q_s	Volumetric rate of sediment transport (Shield's)

APPENDIX A (Continued)

Symbol	Meaning
q_s	Bed-load discharge per unit width
q	Stream discharge per unit width
R	Hydraulic radius
S	Slope
Ss	Specific gravity of sediment
V	Velocity, general
Vm	Mean velocity
γf	Specific weight of fluid
γs	Specific weight of sediment
ν	Kinematic viscosity of fluid
ν_{70}	Kinematic viscosity of fluid at 70°F
ρ	Mass density of fluid
τ_o	Shear stress at boundary
τ_c	Boundary shear stress for beginning of motion
Φ	Intensity of transport
Ψ	Intensity of shear on particle
Σ	Sum of
Δ_p	Percentage of the total weight of a particular grain size fraction

APPENDIX B

SIEVE ANALYSIS OF BED-LOAD MATERIAL

Bridge Creek (As percentage coarser by weight)

Grain size (inches)	Sample 1	Sample 2	Sample 3	Sample 4
2.000	38.27	12.41	15.54	37.74
1.000	58.30	32.85	45.81	59.72
0.750	69.34	41.66	57.79	66.67
0.350	79.87	52.96	71.31	74.81
0.153	87.96	67.81	80.95	80.84
0.111	89.13	70.80	83.60	82.14
0.079	90.24	73.78	86.05	83.28
0.055	91.06	76.14	88.13	84.19
0.039	92.01	78.65	90.15	85.26
0.028	92.93	80.80	91.62	86.29
0.020	93.89	82.90	92.97	87.51
0.014	94.86	84.97	94.15	88.89
0.010	95.73	86.98	95.11	90.38
0.007	96.34	88.64	95.68	91.61
0.005	97.02	90.58	96.18	92.85
0.003	97.69	92.59	96.61	94.07
0.002	98.20	94.25	97.00	95.09
0.002	99.99	99.38	100.00	99.98
Largest particle ("b" axis in inches)	5.2	3.2	4.7	6.1

APPENDIX B (Continued)

SIEVE ANALYSIS OF BED-LOAD MATERIAL

Two O'Clock Creek (As percentage coarser by weight)

Grain size (inches)	Sample 1	Sample 2	Sample 3
2.000	17.02	15.73	8.01
1.000	41.12	38.71	32.33
0.750	50.35	48.09	43.03
0.350	65.24	64.12	55.08
0.153	78.58	79.75	77.68
0.111	80.96	83.35	81.31
0.079	83.05	86.39	84.43
0.055	84.73	88.41	86.48
0.039	86.72	90.33	88.34
0.028	88.56	91.88	89.83
0.020	90.72	93.37	91.37
0.014	92.95	94.74	92.93
0.010	94.90	95.83	94.34
0.007	96.13	96.50	95.33
0.005	97.01	97.03	96.05
0.003	97.55	97.37	96.53
0.002	97.97	97.69	96.93
0.002	99.99	100.00	100.11
Largest particle ("b" axis in inches)	2.5	3.2	4.0

APPENDIX C

BED-LOAD SAMPLING

Date	Time	Sample Duration minutes	Sample Weight lbs.	Sampler* Position	Unit Bed-Load Charge lbs/min/ft.	Mean Water Discharge (for the sampling period) c.f.s.
26 May	15.10	3	20.1	LB	6.7	
	15.15	2	16.6	LB	8.3	
	15.20	2	14.5	LB	7.3	
	15.25	3	23.5	LB	7.8	
	15.30	3	17.0	LB	5.7	16.0
	15.35	4	32.8	LB	8.2	
	15.40	3	23.7	LB	7.9	
	15.45	3	22.5	LB	7.5	
	15.50	4	34.0	LB	8.5	
	15.55	2	14.5	LB	7.3	
26 May	20.25	3	22.8	LB	7.6	
	20.30	3	27.0	LB	9.0	
	20.35	3	6.9	MS	2.3	
	20.40	3	4.8	MS	1.6	
	20.50	3	4.5	MS	1.5	17.5
	20.55	3	35.1	LB	11.7	
	21.00	3	32.7	LB	10.9	
	21.05	3	23.1	LB	7.7	
	21.10	3	30.6	LB	10.2	
	21.15	3	4.5	MS	1.5	
27 May	17.45	3	3.4	MS	1.1	
	17.50	3	0.0	LB	0.0	
	17.55	3	1.8	MS	0.6	
	18.00	3	0.0	RB	0.0	
	18.05	3	2.0	LB	0.7	16.0
	18.10	3	22.8	MS	7.6	
	18.15	3	0.0	RB	0.0	
	18.20	3	7.2	LB	2.4	
	18.25	3	5.4	MS	1.8	
28 May	14.05	3	1.8	LB	0.6	
	14.10	3	0.0	MS	0.0	
	14.15	3	0.0	RB	0.0	13.0
	14.40	10	3.0	LB	0.3	
	14.55	10	0.0	MS	0.0	
	15.10	12	0.0	RB	0.0	

... (Cont'd.)

APPENDIX C (Continued)

Date	Time	Sample Duration minutes	Sample Weight lbs.	Sampler Position	Unit Bed-Load Charge lbs/min/ft.	Mean Water Discharge (for the sampling period) c.f.s.
28 May	15.30	10	12.0	LB	1.2	
	15.45	10	1.0	MS	0.1	13.0
	15.57	10	0.0	RB	0.0	
	16.10	10	13.5	LB	1.3	
28 May	19.20	10	11.7	LB	1.17	
	19.32	10	1.0	MS	0.1	14.0
	19.43	10	0.0	RB	0.0	
29 May	15.45	10	15.0	LB	1.5	
	15.55	10	2.0	MS	0.2	
	16.12	10	0.0	RB	0.0	14.0
	16.20	10	7.5	LB	0.7	
	16.41	10	0.6	MS	0.1	
30 May	14.30	10	2.1	LB	0.2	
	14.40	10	1.9	LB	0.2	
	14.50	10	2.0	MS	0.2	
	15.00	10	1.2	MS	0.12	12.0
	15.10	10	0.0	RB	0.0	
	15.20	10	10.5	MS	1.05	
	15.30	10	10.0	MS	1.0	
30 May	19.05	5	1.3	LB	0.26	
	19.14	5	0.75	MS	0.15	
	19.21	5	0.0	RB	0.0	
	19.26	5	0.5	LB	0.1	
	19.32	5	3.2	MS	0.6	
	19.39	5	7.5	LB	1.5	14.8
	19.45	6	10.8	MS	1.8	
	19.53	5	0.5	MS	0.1	
	19.58	5	3.6	LB	0.7	
	20.16	5	16.8	LB	3.35	
	20.22	5	0.5	MS	0.1	

... (Cont'd.)

APPENDIX C (Continued)

Date	Time	Sample Duration minutes	Sample Weight lbs.	Sampler Position	Unit Bed-Load Charge lbs/min/ft.	Mean Water Discharge (for the sampling period) c.f.s.
31 May	17.16	5	3.5	LB	0.7	
	17.23	5	4.0	MS	0.8	
	17.30	5	0.0	RB	0.0	
	17.36	10	7.4	LB	0.74	
	17.48	10	16.0	MS	1.6	15.0
	18.01	10	20.0	LB	2.0	
	18.13	10	16.0	MS	1.6	
	18.25	10	2.2	MS	0.22	
	18.37	10	22.0	LB	2.2	
6 June	14.00	0.25	23.0	LB	92.0	
	14.25	0.25	12.0	MS	48.0	
	14.27	0.25	7.0	MS	28.0	
	14.30	0.25	10.0	MS	40.0	
	14.40	1.0	25.0	MS	25.0	
	14.45	1.0	25.2	MS	25.2	
	14.48	1.0	34.5	MS	34.0	
	14.50	0.5	23.0	MS	46.0	
	14.53	0.5	25.5	MS	51.0	38.0
	14.55	0.25	36.7	MS	147.0	
	14.58	0.20	34.2	MS	171.0	
	15.00	0.20	14.4	MS	72.0	
	15.04	0.25	8.5	LB	34.0	
	15.05	0.50	6.0	MS	12.0	
	15.07	0.50	0.0	LB	0.0	
	15.08	0.50	20.5	LB	41.0	
	15.11	0.50	9.5	LB	19.0	
6 June	16.15	0.5	10.5	LB	21.0	
	16.18	1.0	14.5	LB	14.5	
	16.19	0.5	14.5	LB	29.0	
	16.22	0.5	0.0	MS	0.0	
	16.25	0.5	27.0	MS	54.0	
	16.27	0.5	28.0	MS	56.0	
	16.28	0.5	22.5	MS	45.0	
	16.31	0.5	0.0	RB	0.0	34.0
	16.36	0.5	14.5	MS	29.0	
	16.39	0.5	8.5	MS	17.0	
	16.41	1.0	4.5	LB	4.5	
	16.44	0.5	7.0	MS	14.0	
	16.46	0.5	0.0	MS	0.0	
	16.49	0.5	3.3	MS	6.6	
	16.50	0.5	0.0	MS	0.0	

... (Cont'd.)

APPENDIX C (Continued)

Date	Time	Sample Duration minutes	Sample Weight lbs.	Sampler Position	Unit Bed-Load Charge lbs/min/ft.	Mean Water Discharge (for the sampling period) c.f.s.
7 June	14.20	1.0	7.8	RB	7.8	
	14.25	1.0	13.0	MS	13.0	
	14.27	1.0	0.0	RB	0.0	
	14.33	1.0	12.0	MS	12.0	
	14.39	1.0	7.0	MS	7.0	
	14.42	1.5	32.5	MS	21.3	
	14.46	1.0	15.5	MS	15.5	
	14.50	2.0	13.5	MS	6.8	28.0
	15.25	1.5	10.5	MS	7.0	
	15.30	1.5	9.5	MS	6.3	
	15.31	1.5	8.5	MS	5.7	
	15.34	1.5	28.5	MS	19.0	
	15.40	1.5	15.5	MS	10.3	
	15.41	1.5	23.5	MS	16.0	
	15.42	5.0	20.0	LB	4.0	
	15.52	5.0	0.0	RB	0.0	
	15.58	5.0	24.5	LB	5.0	
8 June	15.48	2	12.0	LB	6.0	
	15.54	1	2.5	MS	2.5	
	15.56	2	2.5	MS	1.2	
	16.02	2	3.0	RB	1.5	
	16.03	2	10.0	MS	5.0	
	16.06	2	33.0	LB	16.5	26.5
	16.11	2	12.0	MS	6.0	
	16.14	2	27.0	LB	13.5	
	16.18	2	0.0	RB	0.0	
	16.21	2	4.0	MS	2.0	
	16.25	2	13.5	LB	6.8	
9 June	15.00	30	10	MS	0.33	18.5
	15.30	30	15	MS	0.50	
9 June	16.30	60	1	MS	0.0	
10 June	15.00	10	16	LB	0.1	
	15.15	10	0	MS	0.0	16.0
	15.30	10	0	RB	0.0	
	15.45	60	18	LB	0.3	

... (Cont'd.)

APPENDIX C (Continued)

Date	Time	Sample Duration minutes	Sample Weight lbs.	Sampler Position	Unit Bed-Load Charge lbs/min/ft.	Mean Water Discharge (for the sampling period) c.f.s.
12 June	18.00	10	1.5	MS	0.15	
	18.15	11	4.5	LB	0.41	18.5
	18.30	10	0.0	RB	0.0	
22 June	20.00	2	0.0	LB	0.0	
	20.05	4	0.0	MS	0.0	
	20.10	4	5.5	RB	1.1	24.0
	20.15	3	0.0	LB	0.0	
	20.20	3	6.8	MS	2.3	
	20.25	3	0.0	RB	0.0	

* LB - Left Bank
MS - Mid-Stream
RB - Right Bank